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Quantification of Criteria and Air Toxic Pollutants in Biodiesel Exhaust using Fourier Transform Infrared Spectroscopy

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Quantification of Criteria and Air Toxic Pollutants in Biodiesel Exhaust using Fourier Transform Infrared Spectroscopy

Flora Su
Faculty Advisor: Dr. Britt Holmén

August 1, 2015

Honors Thesis Report

Contents

List of Figures

List of Tables

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1. Introduction

1.1 Executive Summary

In recent years, the push for renewable energy has led to increasing popularity in replacing petroleum diesel (petrodiesel) with biodiesel. While known to reduce most regulated air pollutants, including carbon monoxide (CO) and particulate matter (PM), as well as unburned hydrocarbons (HC), some studies have shown that biodiesel combustion may increase other pollutant emissions, such as oxides of nitrogen (NO_x) and mobile source air toxics (MSATs). The relationship between biodiesel fuel content and MSAT emissions remains largely inconclusive. Some studies suggest that carbonyl emissions (such as the MSAT compounds formaldehyde and acetaldehyde) may increase due to the oxygenated nature of biodiesel fuel, while others claim that biodiesel combustion can reduce carbonyl emissions.

This study focused on evaluating the effects of using biodiesel fuel blends in place of petrodiesel in a light-duty diesel engine on the gaseous exhaust emissions of five pollutants: CO, CO_2, NO, NO_2, and formaldehyde (an MSAT). Engine tests were conducted using an engine dynamometer with a Volkswagen 1.9L SDi industrial diesel engine at the University of Vermont from June-October 2013 of waste vegetable oil (WVO) and soybean (SOY) biodiesel exhaust for B0, B10, B20, B50, and B100 blends. The emissions data were collected using Fourier Transform Infrared (FTIR) spectroscopy at 1-Hz temporal resolution, and the infrared spectra were processed using MKS MultiGas 2030 High Speed software. The drive cycle used in the experiment was developed in the TAQ Lab with multiple phases to simulate real-world, transient driving behavior, as well as steady-state driving at three different engine load settings (based on engine speed and throttle position). Statistical analyses were conducted on the steady-state emissions to determine whether or not the emissions rates were significantly affected by the biodiesel feedstock, fuel blend, and drive cycle phase (a surrogate for the engine operating conditions). Each of these factors had a significant effect on the exhaust emissions of all five pollutants. The specific effect of each of these factors were also evaluated in detailed and compared to existing literature.

Following the steady-state analysis, log-linear models were produced using JMP statistical software to predict the transient phase emissions for each pollutant based on three engine operating parameters (percent load [%)], engine speed [rpm], and exhaust temperature [^oC]) and biodiesel fuel content (%). The models for CO_2 ($R^2 \approx 0.80$) and NO ($R^2 \approx 0.74$) exhibited the best fit, while NO_2 ($R^2 \approx 0.54$) and CO ($R^2 \approx 0.48$) could be modeled moderately well. Formaldehyde ($R^2 \approx 0.28$) posed the greatest challenge for predicting emissions, especially for high ER values. Each model was then validated using the transient phase data for a run whose data had been excluded from the regression analysis used to develop the model.

The results of this analysis showed that CO_2 and NO emission rates could be modeled fairly well using three engine operating parameters and the biodiesel fuel content (%). The log-linear models had the most difficulty with fitting formaldehyde and CO emissions, both of which are products of incomplete combustion. Additional variables or separate models for different modes of engine operation may be necessary for predicting emissions of these pollutants.

1.2 Objectives

The primary research questions explored by this study were as follows:

1. How do biodiesel fuel blends affect the gaseous engine-out exhaust emissions of a light-duty diesel engine?
2. How much do the biodiesel feedstock and engine operating conditions affect the emissions?
3. Can the emissions produced by transient driving behavior be modeled based on biodiesel fuel blend, engine speed, percent load, exhaust temperature, and biodiesel feedstock?

For this study, five gas-phase pollutants were selected for the analysis: carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x – specifically, NO and NO_2), and formaldehyde. To answer these research questions, two separate statistical analyses of the emissions produced by steady-state and transient driving were conducted:

1. **Steady-State Driving Analysis – Two-Way ANOVA, Student's t-Test**
   Two-way ANOVA tests were conducted using the steady-state phase emissions data to determine the effects of biodiesel feedstock, fuel blend, and engine operating conditions (drive cycle phase). This revealed how strongly each of the three factors affected the emissions concentrations, as well as the interactive effect of the factors. Pairwise student's t-tests were also conducted to confirm the findings of the two-way ANOVA tests.

2. **Transient Driving Analysis – Multivariate Regression Analysis**
   The findings of the steady-state analysis were applied to develop a model for predicting the transient phase emissions for each of the five pollutants. A multivariate regression analysis of the transient cycle data was conducted to produce a model using engine operating parameters (percent load (%), engine speed (rpm), and exhaust temperature (^oC)) as input variables to predict emission rates.

2. Background and Literature Review

2.1 Chemistry of Diesel and Biodiesel

When diesel engines were first invented, it was more common to use vegetable oil as the fuel source rather than petroleum diesel because methods of extracting petroleum diesel were not yet sufficiently developed enough to meet the fuel demand (Pacific Biodiesel, 2015). Vegetable oil consists of *triglycerides*, which contain three *fatty acid tails.* An example of such a triglyceride is shown below in **Figure 2-1**:

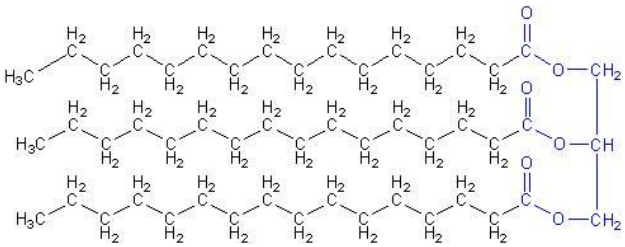

Figure 2-1: Vegetable oil triglyceride (Goshen College, 2014). The blue-highlighted component shows the glycerol group in the molecule; the black carbon-hydrogen chains are fatty acids.

Note that triglycerides, with their three hydrocarbon chains, are fairly large molecules. The sheer bulk of the molecules causes them to have a greater tendency to "stick" together – it is more difficult for the molecules to slide past each other. In cold weather this becomes a problem, as vegetable oil tends to gel in cooler temperatures, making it less suitable for use in an engine (Goshen College, 2014).

One method of breaking fatty acids into smaller molecules that are better suited for use as engine fuel is a process known as *transesterification*. Transesterification is the chemical reaction between a fatty acid and an alcohol, such as methanol, which causes the three hydrocarbon chains in the fatty acid to break apart. An example of transesterification is diagrammed in **Figure 2-2:**

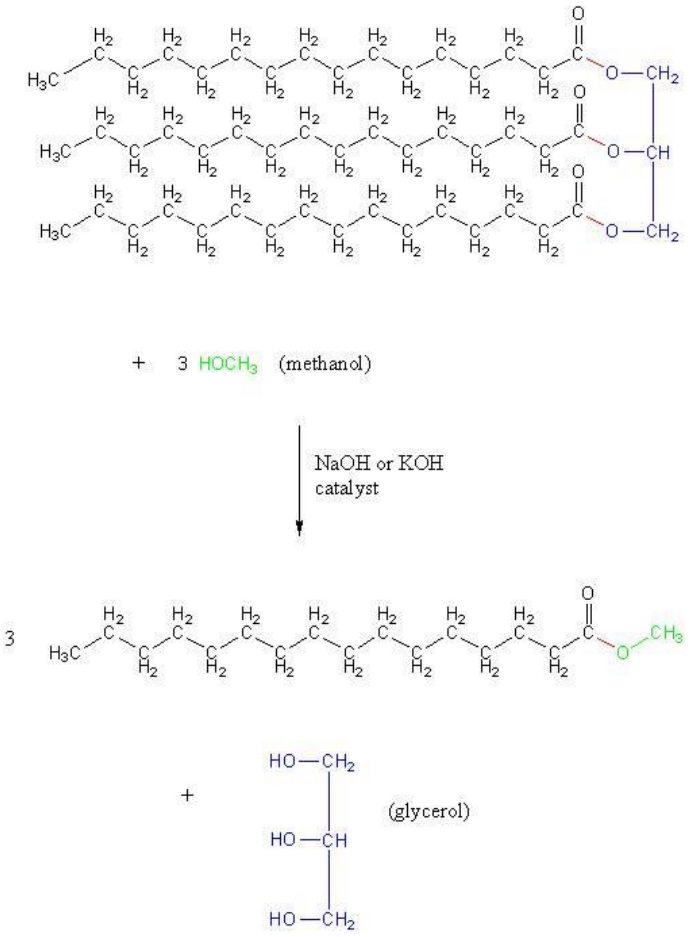

Figure 2-2: Transesterification of a fatty acid (Goshen College, 2014)

As seen in **Figure 2-2,** transesterification of one fatty acid yields three oxygenated hydrocarbon chains and glycerol. The oxygenated portion of the hydrocarbon chains are *ester functional groups* (shown in green in **Figure 2-2**). Because the oxygenated hydrocarbon chains were formed from a fatty acid and contain an ester, they are known as *fatty acid methyl esters*, or FAMEs. FAMEs are the constituents of a more suitable fuel for engines: biodiesel.

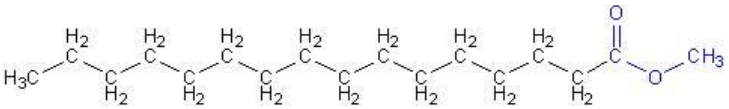

Figure 2-3: Biodiesel fatty acid methyl ester (FAME) (Goshen College, 2014)

Nowadays, biodiesel can be formed not only from virgin or waste vegetable oils, but also from animal oils and non-edible plant oils (Knothe, 2001). Some researchers have also developed methods of producing biodiesel from other sources, or *feedstocks*, including novel sources such as monosodium glutamate derived from microbial oils in microorganisms found in wastewater (Xue et al., 2006).

Petroleum diesel, on the other hand, is comprised mostly of aliphatic hydrocarbons, or straight-chain alkanes. An example of a diesel n-alkane molecule is shown in **Figure 2-4**:

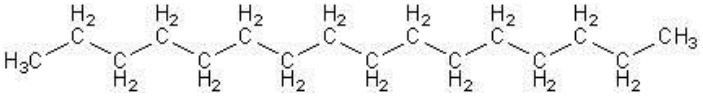

Figure 2-4: Diesel hydrocarbon molecule (Goshen College, 2014)

Note that the diesel molecule consists only of carbon and hydrogen atoms and lacks the oxygen atoms characteristic of the ester found in biodiesel. In other words, the FAME is an oxygenated version of the hydrocarbon chain – it is at a higher level of oxidation. This is an important property that will help with interpreting the trends observed in biodiesel exhaust emissions.

Because the FAMEs found in biodiesel are very similar in structure to the hydrocarbons in diesel, most existing diesel engines are capable of using blends containing up to 20 percent biodiesel with no modifications (McCormick et al., 2009). Some engines can use pure biodiesel with few or minor modifications, because the biodiesel may react with and weaken rubber tubing (Goshen College, 2014).

2.2 Biodiesel and Air Quality

In recent years, the push for renewable energy has led to increasing popularity in biodiesel use in place of petroleum diesel (or "petrodiesel") due to its renewable and biodegradable nature. It also serves as an easily implementable domestic alternative to imported petrodiesel fuel. Biodiesel use is also expected to increase as in response to the Energy Independence and Security Act of 2007, which requires the use of 36 billion gallons of biofuels in the transportation fuel market by 2022 (Karavalakis et al., 2014). Additionally, biodiesel is generally superior to petrodiesel in many fuel qualities, such as a higher flash point, inherent lubricity, and a reduction in most regulated pollutant emissions (Knothe, 2008). As a result of its growing popularity, it is becoming increasingly more important to understand the health and environmental impacts of biodiesel use (Knothe, 2008). Studies have shown that biodiesel exhaust emissions generally have significantly lower concentrations of many of the regulated "criteria" gas emissions, such as carbon monoxide (CO), particulate matter (PM), and sulfates (Karavalakis et al., 2009a, 2009b; Lapuerta et al., 2008; Roy et al., 2013). Biodiesel exhaust has also been shown to contain lower amounts of unburned hydrocarbons (HC), which has been attributed to an increase in fuel combustion efficiency due to the presence of oxygen in biodiesel fuel (Roy et al., 2013). However, there is evidence that biodiesel exhaust may contain elevated concentrations of nitrogen oxides (up to 2% increase) and

other hazardous compounds such as mobile source air toxics (DOE, 2013; EPA 2002; Knothe, 2008). **Figure 2-5** shows a graph produced by the EPA in 2002, which describes the percent change in exhaust emissions for three regulated air pollutants (CO, PM, and NO_x), as well as for HC.

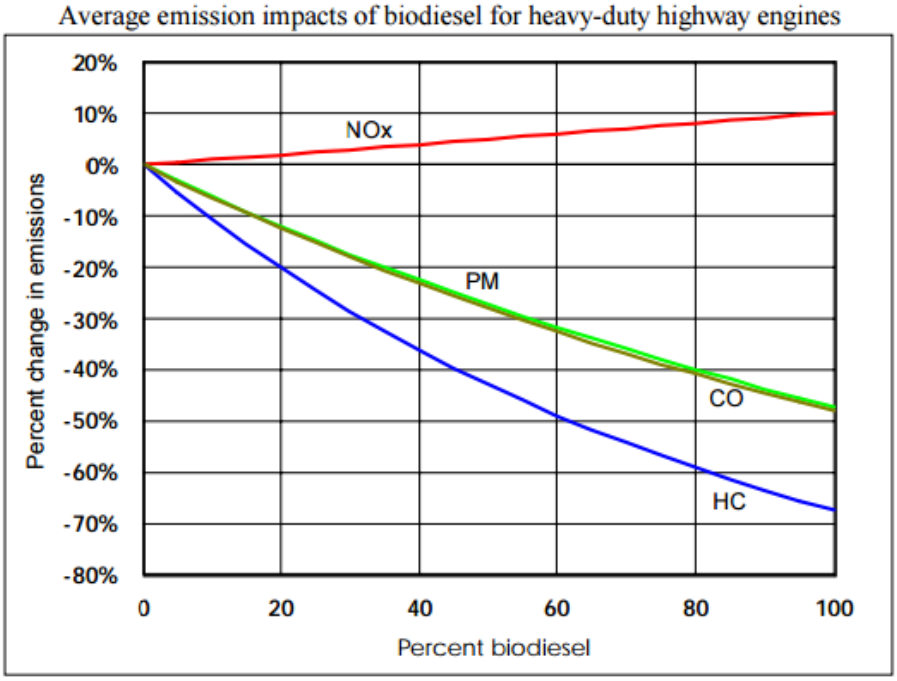

Figure 2-5: Average emission impacts of biodiesel for heavy-duty engines (EPA, 2002)

It is important to note that the existing body of research is limited primarily to studies on heavy-duty diesel (HDD) engines and vehicles, including trucks, buses, and tractors (Corrêa et al., 2008; Guarieiro et al., 2008; Jakober et al., 2008), which is reasonable given that the majority of the diesel vehicle fleet consists of heavy-duty vehicles. Relatively few studies have explored the effects of biodiesel use with light-duty diesel engines and vehicles. Because the light-duty diesel vehicle population is expected to increase in the near future (Karavalakis et al., 2014; Tsai et al., 2012), it is crucial to study the effects of biodiesel use in light-duty diesel vehicles.

In addition, the impact of biodiesel use on certain unregulated pollutants, such as mobile source air toxics, is not as thoroughly studied and understood as the effects on criteria pollutants. Mobile source air toxics (MSATs) are defined by the U.S. Environmental Protection Agency (EPA) as compounds emitted from vehicular traffic that pose serious health risks (EPA, 2013). Many MSATs are carcinogenic, while non-carcinogenic MSATs can severely damage the neurological, cardiovascular, respiratory, immune, and reproductive systems (EPA, 2013; ATSDR 2014). According to a 2005 study conducted by the EPA, the MSATs that contributed the most to cancer risks nationwide were formaldehyde and benzene. Acrolein, a respiratory and dermal irritant, was identified as the primary MSAT responsible for non-cancerous health risks. Formaldehyde is also of particular interest because it constitutes 50-70 percent of the total vehicular carbonyl emissions (EPA, 1999). It is ranked as an EPA Group B1 carcinogen, or a probable human carcinogen (EPA, 2013). Additionally, it is a precursor of photochemical ozone (EPA, 1999), which is a primary component of photochemical smog and is known to have detrimental effects on human, animal, and plant health. Ground-level ozone can permanently damage the lungs and heart, especially in

the young and elderly, causing short- and long-term problems including coughing, wheezing, bronchitis, pneumonia, heart attacks, lung cancer, premature aging of the lungs, and death (Oblack, 2015).

The presence of MSATs in biodiesel exhaust emissions indicates a need for evaluating the benefits and hazards of replacing petrodiesel with biodiesel. As noted by Corrêa and Arbilla (2008), biodiesel is an ester (as opposed to diesel, which consists primarily of saturated hydrocarbon chains). Some studies have suggested that the presence of oxygen atoms in biodiesel could increase its potential for producing certain MSATs, such as carbonyl compounds. Previous studies have shown that the two most prevalent carbonyl compounds found in biodiesel emissions were formaldehyde and acetaldehyde (Corrêa and Arbilla, 2008; Turrio-Baldassarri et al., 2004). Other carbonyl emissions that have been found in biodiesel exhaust emissions include acrolein, acetone, benzaldehyde, butyraldehyde, crotonaldehyde, and propionaldehyde (Cazier et al., 2010; Corrêa and Arbilla, 2008; Turrio-Baldassarri et al., 2004). Processes that produce carbonyl emissions during vehicle operation include incomplete combustion and oxidation of hydrocarbons on the oxidation catalyst (Bikas and Zervas, 2007).

The effect of replacing diesel with biodiesel on air toxics emissions is not yet clearly understood because the incredible variety of testing conditions (engine year/model used, drive cycle, sampling and analysis methods, biodiesel feedstock, and so on – although engine/vehicle type has largely focused on heavy-duty diesel) renders drawing comprehensive conclusions based on comparisons between studies difficult (Karavalakis et al., 2009b). Turrio-Baldassarri et al. (2004) also suggested that many chemical characteristics of the fuel may have an effect on carbonyl and light aromatic emissions, including chain length, the number and presence of unsaturated carbons, purity level, and the nature of impurities in the fuel.

However, there are some related factors whose effects on carbonyl emissions have been shown to be largely consistent between studies. Many studies have shown that the model and year of the engine has a significant effect on exhaust emissions. Newer technologies, such as newer vehicle models, improved fuel composition (low-sulfur and ultra-low sulfur diesel), and advanced engine technologies have been shown to effectively reduce carbonyl emissions (Jakober et al., 2008; Grimes et al., 2011). In addition, many studies agree that higher engine loading and exhaust temperatures promote more complete combustion, which can reduce carbonyl emissions. The driving behavior, which is simulated using drive cycles, also has a significant effect on the efficiency of fuel combustion, which in turn affects the amounts of carbonyls produced. In general, urban drive cycles have been found to promote higher emissions of volatile organic compound (VOC) and carbonyl pollutants, while highway drive cycles exhibit lower emissions (Cazier et al., 2010; Karavalakis et al., 2011b). This is because engines undergoing an urban drive cycle experience more transient driving conditions, which can cause higher emissions as a result of frequent acceleration, deceleration, and stopping/idling events. These driving conditions produce a "cold-start" effect, during which the oxidation catalyst is partially deactivated, which results in higher hydrocarbon emissions (Karavalakis et al., 2011b). Highway driving behavior, on the other hand, involves higher engine speed and loading, which produces conditions more suitable to improved combustion efficiency. The increased engine speed and engine load also increases the exhaust temperature, which also improves the oxidation catalyst efficiency. These combined

effects result in a reduction in the formation of products of incomplete combustion, such as carbonyls (Karavalakis et al., 2011b).

While many points of agreement can be found regarding the effect of engine technology and operating conditions on carbonyl emissions, the effect of replacing diesel with biodiesel is well-disputed between studies. As mentioned earlier, biodiesel consists of fatty acid methyl esters, whereas petrodiesel consists mostly of aliphatic hydrocarbons. The primary difference between these two types of molecules is that esters contain oxygen atoms, whereas alkanes do not. Studies that observe an increase in carbonyl emissions claim that biodiesel has a greater tendency to produce oxygenated exhaust compounds such as carbonyls because biodiesel is an oxygenated fuel (Corrêa and Arbilla, 2008).

However, other studies suggest that the oxidized property of biodiesel esters would promote more complete combustion, and thus result in a *decrease* in carbonyl emissions (Guarieiro et al., 2008; Roy et al., 2013). This explanation is based on chemical mechanisms regarding combustion. When organic substances undergo combustion, the process is inherently an oxidative process. The straight-chain alkanes found in diesel fuel contain no oxygen molecules, and are thus at a low oxidation state. When undergoing combustion, alkanes are converted to alcohols, which are then converted to carbonyl compounds, then to carboxylic acids, then to esters, and then finally to carbon dioxide (Guarieiro et al., 2008). This process is diagrammed in **Figure 2-6**:

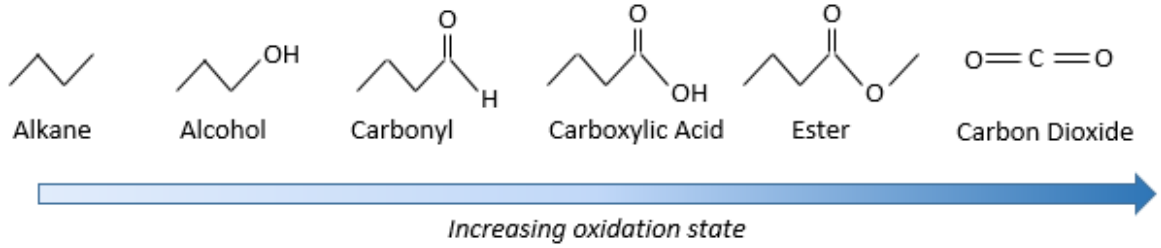

Figure 2-6: Oxidation of organic compounds during combustion

As seen in **Figure 2-6**, alkanes are at the lowest oxidation state. Since no real engine system operating using air as the oxidant is efficient enough to promote complete combustion all the time, a very specific set of conditions must be present to convert alkanes (which constitute pure diesel) into carbon dioxide. Esters (which make up biodiesel), on the other hand, are at a much higher level of oxidation, and thus are more prone to undergo complete combustion and become converted into carbon dioxide. Therefore, based on this chemical pathway, biodiesel should be more likely to undergo complete combustion than pure diesel, and thus fewer intermediate compounds such as carbonyls should be produced during engine operation, assuming identical combustion conditions (Guarieiro et al., 2008). A 2013 study by Roy et al. included an analysis of the brake specific fuel consumption to determine the fuel conversion efficiency (how effectively fuel is transformed into usable energy) for canola biodiesel blends of B5, B10, B20, B50, and B100. The analysis showed that all the canola biodiesel fuel blends had a higher fuel conversion efficiency than pure petroleum diesel fuel. In addition, the fuel conversion efficiency increased with biodiesel fuel content (Roy et al., 2013). The improved fuel conversion efficiency thus suggested that biodiesel fuels promote better fuel combustion, which should in turn reduce CO and unburned hydrocarbon (HC) emissions (Roy et al., 2013). This improvement in fuel combustion was also attributed to the higher oxygen content of biodiesel.

2.3 Typical Methods for Quantifying Biodiesel/Diesel Exhaust Gas-Phase Components

Common methods for determining diesel and biodiesel exhaust gas-phase composition include gas chromatography – mass spectrometry (GC-MS), gas chromatography with flame ionization detection (GC-FID), and high-performance liquid chromatography with UV detection (UV-HPLC). Many researchers use EPA standard (Method TO-11A) for measuring carbonyl compounds (aldehydes and ketones), including formaldehyde. This involves the use of 2,4-dinitrophenylhydrazine (2,4-DNPH) coated on adsorbent silica cartridges to capture carbonyl compounds, followed by separation and analysis of the hydrazone derivative using UV-HPLC.

While each of these methods can be effectively used to identify and quantify the constituents of exhaust emissions samples, problems with the quality of sample collection are sometimes reported. For instance, a sampling and analysis quality control program conducted by Cahill and Okamoto (2012) reported difficulty with measuring gas-phase acetaldehyde using GC-MS. The recovery of acetaldehyde ranged from 4.8 to 20.3 percent for animal, renewable, and soy biodiesel fuels. Such low recovery and inconsistency led to the exclusion of acetaldehyde in the study – even though it was the single most abundant chemical detected. The cause of low acetaldehyde recovery was attributed to blow-off during sample collection (Cahill and Okamoto, 2012). Jakober et al. (2008) also noted that using *O*-(2,3,4,5,6-pentafluorobenzyl)hydroxylamine (PFBHA) derivatization in conjunction with gas chromatography-ion trap mass spectrometry (GC-ITMS) and high-performance liquid chromatography-ion trap mass spectrometry (HPLC-ITMS) was incapable of measuring formaldehyde and acetaldehyde, the most volatile carbonyl species. This was attributed to their high vapor pressures and poor retention by the annular denuders (Jakober et al., 2008). Additionally, GC-MS may be a powerful tool for identifying and quantifying compounds, but it is unsuitable for rapid high-sensitivity analysis (Krone et al., 2010), which may be crucial for time-varying measurements, such as the concentration of exhaust emissions during transient engine operation.

2.4 Fourier Transform Infrared Spectroscopy

This research study used a novel method of applying infrared spectroscopy to identify and quantify the gas-phase components of biodiesel exhaust emissions. Fourier transform infrared (FTIR) spectroscopy involves measuring the absorbance (or transmittance) of infrared radiation as it is passed through a sample. The degree of absorbance is affected by the types of chemical bonds between atoms in a compound, which is unique to each compound. As a result, every molecule has a unique absorption "fingerprint" that can be used to identify its presence in a sample (Thermo Nicolet Corp., 2001). One major advantage of FTIR spectroscopy is that measurements can be made on a second-by-second basis, providing higher resolution data that allows for more in-depth analysis of the behavior of the gaseous emissions over the course of the engine drive cycle. FTIR spectroscopy is also more sensitive than most other detection and quantification methods (Thermo Nicolet Corp., 2001).

However, FTIR methods may not be the perfect method for biodiesel exhaust. Traditionally, infrared spectroscopy was used as a *qualitative* method for identifying compounds. The peaks in the spectra are produced by vibrations between the molecular bonds, which can indicate the types of functional groups present in the molecule, but a single peak cannot be used to identify a molecule. Rather, an entire pattern of peaks must be considered – just as the whole fingerprint pattern must be used to identify a person, rather than a single ridge. Consequently, it is fairly easy

to identify compounds in pure or nearly pure mixtures, but complications arise when multiple compounds are present, especially if the compounds contain similar functional groups.

A previous analysis conducted by the researcher during the summer 2014 of FTIR-quantified exhaust components of B10, B20, B50, and B100 fuel blends of waste vegetable oil (WVO) biodiesel revealed that formaldehyde constituted the majority of the MSAT emissions, while acetaldehyde was measured below the detection limit in less than 5% of the measurements (Su, 2014). The low acetaldehyde measurements were inconsistent with the findings of previous studies, which suggest that both formaldehyde and acetaldehyde are two of the most prevalent carbonyl components of biodiesel and diesel exhaust (Cazier et al., 2010; Corrêa and Arbilla, 2008; Guarieiro et al., 2008; Karavalakis et al., 2011b; Magara-Gomez et al., 2012; Peng et al., 2008), including studies on light-duty diesel vehicle emissions (Cazier et al., 2010; Tsai et al., 2012). One potential source of error in the prior analysis may have resulted from spectral interference caused by similarities in the molecular structure of formaldehyde and acetaldehyde (**Figure 2-7** and **Figure 2-8**, respectively). For each molecule, the left side shows the Lewis structure, while the right side shows the ball-and-stick 3D model.

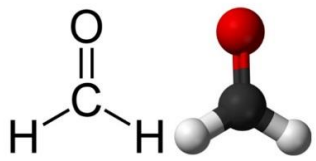

Figure 2-7: Formaldehyde molecular structure (EMF, 2015)

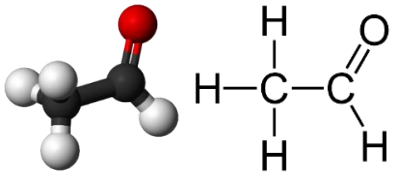

Figure 2-8: Acetaldehyde molecular structure (Wikimedia, 2006)

As these figures show, both formaldehyde and acetaldehyde are light aldehydes. As aldehydes, both contain the carbonyl functional group (C=O) at the end of the hydrocarbon chain (or, in the case of formaldehyde, on its single carbon atom). The primary difference between formaldehyde and acetaldehyde is the replacement of a methyl group for one of the hydrogen atoms on the formaldehyde molecule. Because IR spectroscopy measures the response of a molecule, which is largely affected by the presence of functional groups and certain bonds within the molecule, the structural similarity between formaldehyde and acetaldehyde could be expected to produce similar IR spectra.

A representative IR spectrum for formaldehyde and acetaldehyde from the default MKS calibration database are shown in **Figure 2-9** on the following page:

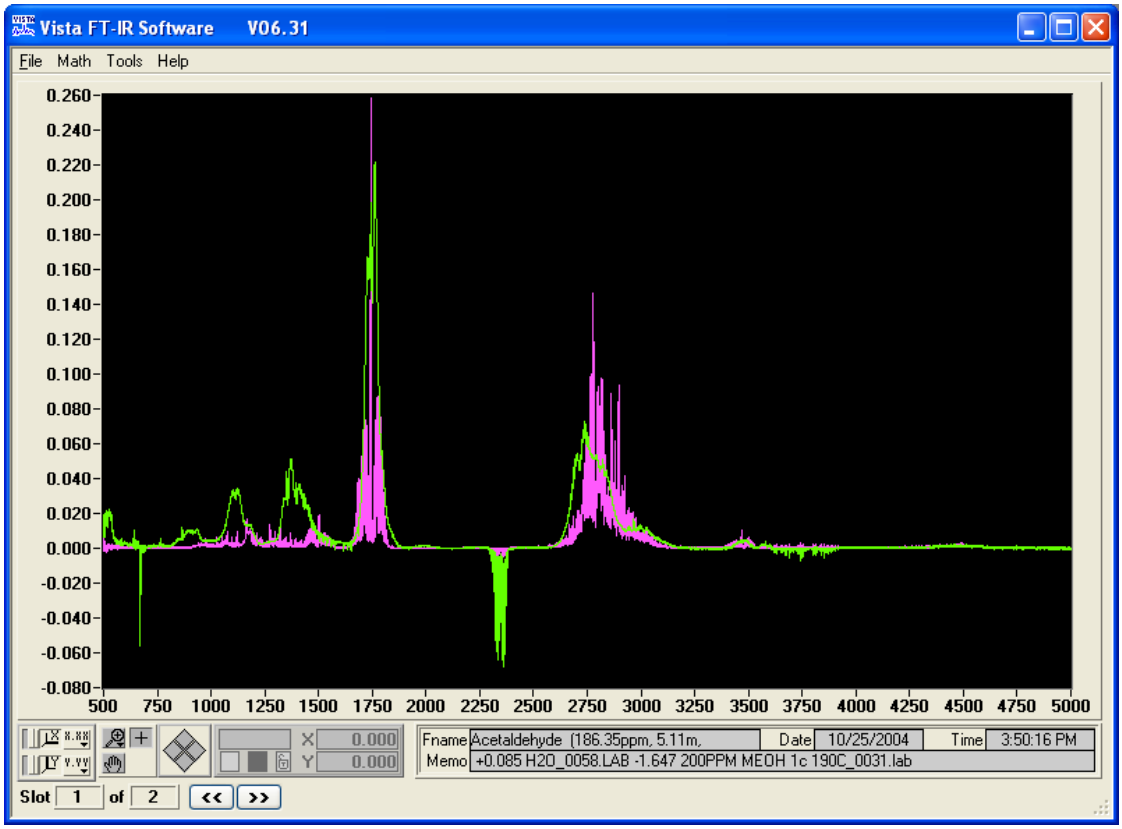

Figure 2-9: Sample default calibration spectra for acetaldehyde (green, 186.35ppm) and formaldehyde (pink, 69.0ppm), measured at 191°C with a pathlength of 5.11m.

On the infrared spectrum, the carbonyl stretch (C=O) of saturated aldehydes has a characteristic peak from 1740-1720 cm^{-1} (University of Colorado, 2015), which can be clearly seen for both formaldehyde and acetaldehyde. In addition, the O=C-H stretch produces a diagnostic band, which can appear as one or two bands in the 2830-2695 cm^{-1} region (University of Colorado, 2015). Both acetaldehyde and formaldehyde are light saturated aldehydes, which means they share these same diagnostic bands. The MKS software used for analyzing the data used two relatively broad regions for quantifying acetaldehyde, while six narrower spectrum bands are used for quantifying formaldehyde. **Table 2-1** below shows the spectral regions used for identifying and quantifying formaldehyde and acetaldehyde concentrations. A table showing all of the regions used for all the compounds listed in the April 2013 method (described in detail under **Section 3: Data**)

Table 2-1: Regions used for identification and analysis of formaldehyde and acetaldehyde, placed in order by location along the IR spectrum and aligned to show overlap

Formaldehyde			Acetaldehyde		
Region #	Band Range		Band Range		Region #
Region 01	885.18	1584.5	813.1	1915.23	Region 01
Region 02	1665.74	1817.37			
Region 03	2545.13	2671.45	2576.47	2863.57	Region 00
Region 00	2671.69	2785.47			
Region 04	2785.71	3123.2			
Region 05	3348.35	3562.66	2863.81	3664.13	Region 02

Figure 2-10 and **Figure 2-11** illustrate how these two compounds might interfere with each other by displaying the calibration spectra produced from the highest concentration sample of one compound, and then loading the spectrum of the interfering compound using a sample with the closest concentration.

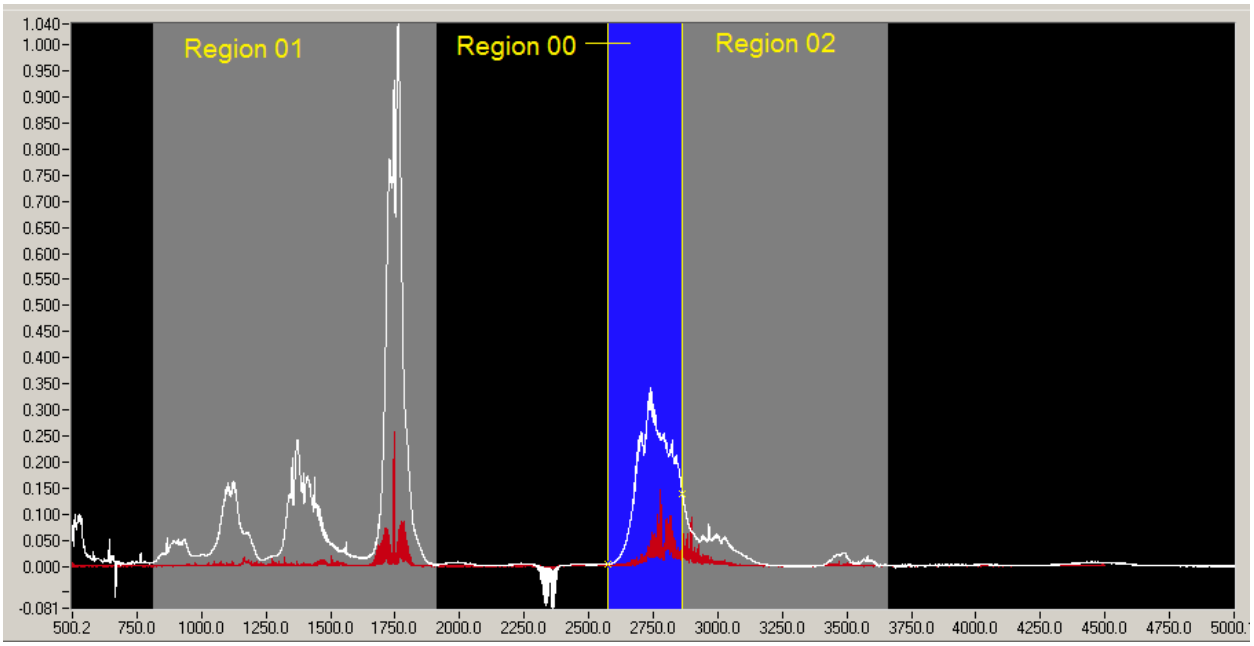

*Figure 2-10: The default calibration spectrum for **acetaldehyde** (931.74 ppm, in white, whose regions are highlighted) and formaldehyde (69.0 ppm, in red) loaded in the region editor as an interference.*

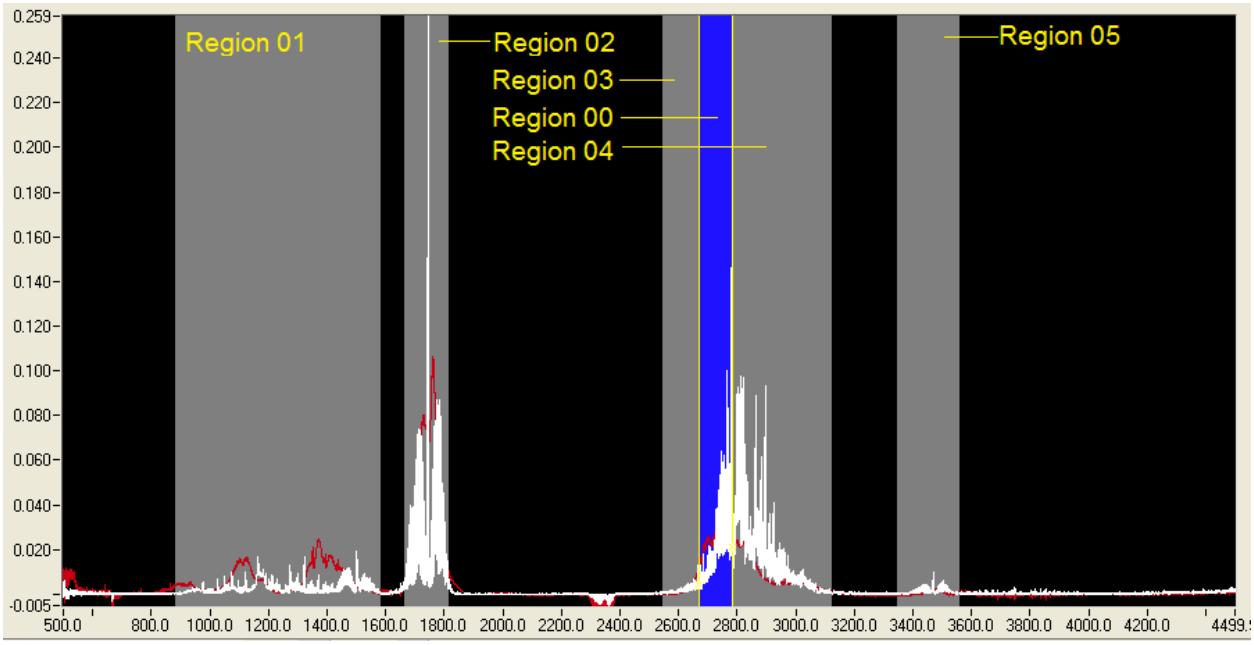

*Figure 2-11: The default calibration spectrum for **formaldehyde** (69.0 ppm, in white, whose regions are highlighted) and acetaldehyde (93.17 ppm, in red) loaded in the region editor as an interference.*

Due to the researcher's limited experience with IR spectroscopy, it was not possible to investigate whether or not spectral interference may have resulted in low detection of acetaldehyde. While the

literature has shown that both acetaldehyde and formaldehyde are both major components of carbonyl emissions from diesel and biodiesel, for this analysis it was sufficient to study only the trends for formaldehyde emissions. Because both formaldehyde and acetaldehyde are very light carbonyls and are chemically similar, the observed effects of the studied factors on formaldehyde emissions will likely be similar to those for acetaldehyde as well. In addition, most studies on carbonyl emissions in diesel and biodiesel exhaust for heavy-duty and light-duty diesel vehicles have shown that formaldehyde has often been measured in greater amounts than acetaldehyde (Corrêa and Arbilla, 2008; Magara-Gomez et al., 2012; Peng et al., 2008). In some studies, the emission rates (mg km^{-1}) of acetaldehyde are similar to or slightly higher than those measured for formaldehyde. For example, Karavalakis et al. (2011b) reported acetaldehyde emission rates between 0.491-0.714 mg km^{-1}, while formaldehyde emission rates fell between 0.488-0.731 mg km^{-1} for used frying oil methyl ester biodiesel in a Euro 4 diesel passenger car operating on the New European Driving Cycle (NEDC). However, the majority of studies reported significantly higher formaldehyde emission rates, and thus it would suffice to use formaldehyde as a representative of light carbonyl MSATs in this study.

2.5 Mobile Source Air Toxic Emissions Modeling

One of the most widely-used emissions modeling program used in the U.S. is the Motor Vehicle Emission Simulator (MOVES), an emission modeling system released by the EPA for assessing the air quality impacts of transportation projects (EPA, 2015). MOVES can estimate vehicle emissions of greenhouse gases, criteria pollutants, and some mobile source air toxics (MSATs) (EPA, 2015). However, the current version of MOVES (MOVES2014) is limited in its ability to model emissions for light-duty diesel engines running on biodiesel fuel blends. MOVES2014 estimates formaldehyde and other air toxics by first producing an estimate of the total volatile organic compound (VOC) emissions, and then multiplying it by a "toxic fraction" determined from speciated emissions data from the Advanced Collaborative Emissions Study (ACES) (EPA, 2014). The data from the study are based on diesel-powered, heavy-duty vehicles, but the same toxic fractions are applied to light-duty vehicles with the same model year distinction (EPA, 2014). Use of biodiesel fuel also has no effect on the toxic fractions (EPA, 2014). One objective of this study was to develop emissions models for a light-duty diesel engine based on measurable engine operating parameters and that also accounts for biodiesel fuel content.

3. Data

3.1 Engine and Fuel Information, Drive Cycle, and Test Run Sequence Information

The data used in this study were previously collected using the procedures described in TRC Report 14-008 (Holmén et al., 2014) by the Transportation and Air Quality (TAQ) Lab at the University of Vermont between June 2013 and May 2014. A CM-12 light-duty diesel engine test bed (Armfield Ltd), consisting of an eddy current dynamometer with a Volkswagen 1.9L SDi industrial diesel engine, was run using both waste vegetable oil (WVO) biodiesel and soybean (SOY) biodiesel blends. The WVO and SOY biodiesel fuels were produced by the University of Connecticut and blended with petroleum diesel (petrodiesel) fuel at the University of Vermont. The biodiesel fuels used were tested for conformation to ASTM standards, and both passed except for WVO with respect to cold soak properties and total sodium/potassium content. The biodiesel fuels were blended with ultra-low sulfur diesel (ULSD) purchased from Trono Fuels in Burlington, VT. However, a different batch of petrodiesel was used with each type of biodiesel (WVO and SOY), which may have introduced an additional source of variation between the fuel blends for each feedstock.

The two biodiesel fuels were blended with ULSD to produce fuel blends of B0, B10, B20, B50, and B100, where B0 is 0% biodiesel (100% petroleum diesel) and B100 is 100% biodiesel. Each blend was tested at least in triplicate. A summary of the data collection is provided in **Table 3-1**. **Table 3-1** also includes notes on data collection problems experienced for each run. Runs highlighted in red were excluded from the analysis, which is discussed later in the "3.3 Data Quality Checks: 3.3.2 Abnormal Run Data" section.

Table 3-1: Data collection record for all test runs.

Feedstock	Run # in 01AUG2014 dataset	Test Date	Bio%	Notes on quality of data / problems with data collection
WVO	1	18-Jun-2013	0	
WVO	2	25-Jun-2013	0	Manual inspection of raw spectra revealed an anomalous "kink" in the baseline of the spectra near the end of the run
		5-Aug-2013	0	*Missing Dil Ratio Data
WVO	3	6-Aug-2013	0	*FTIR Pump off short time
WVO	4	29-Aug-2013	10	*Deleted 5Gas Run Data - does not affect FTIR data
WVO	5	30-Aug-2013	10	
WVO	6	31-Aug-2013	10	
WVO	7	4-Sep-2013	20	
WVO	8	5-Sep-2013	20	
WVO	9	6-Sep-2013	20	
WVO	10	9-Sep-2013	50	
WVO	11	10-Sep-2013	50	
WVO	12	11-Sep-2013	50	
WVO	13	19-Sep-2013	100	*5Gas software crashed - does not affect FTIR data
WVO	14	20-Sep-2013	100	
WVO	15	20-Sep-2013	100	
WVO	16	22-Oct-2013	0	
WVO	17	24-Oct-2013	0	
WVO	18	25-Oct-2013	0	*EEPS - no post-IB - does not affect FTIR data
		4-Dec-2013	0	
		5-Dec-2013	0	
		6-Dec-2013	0	
		6-Dec-2013	0	
SOY	19	1-May-2014	0	Trono #2 "Aged" B000 Run/ Erroneous Dilution Pressure for part of the run due to BNC connector short
SOY	20	2-May-2014	0	after run topped off w/ N2 and re-stored in cold
SOY	21	5-May-2014	10	
SOY	22	6-May-2014	10	
SOY	23	6-May-2014	10	Topped off w/ Bucket 66 (N2 headspace; stored in 104C)
SOY	24	7-May-2014	20	Errored out after Scheduler; NO STEADY STATES
SOY	25	7-May-2014	20	*QFF493 striped pattern/ Erroneous Dilution Pressure due to BNC connector short/ Data suggests that ice bath for dilution oil may have melted
SOY		12-May-2014	20	Did not log SCANTOOL
SOY	26	12-May-2014	20	
SOY	27	13-May-2014	20	Raw FF pump not connected; diluted raw samples
SOY	28	13-May-2014	20	
SOY	29	14-May-2014	20	Everything collected - very high DR - Erroneous Coolant Temperature
SOY	30	15-May-2014	20	1st run with thermocouple verification of coolant
SOY	31	20-May-2014	50	
SOY	32	20-May-2014	50	
SOY	33	22-May-2014	50	
SOY	34	23-May-2014	100	
SOY	35	23-May-2014	100	
SOY	36	26-May-2014	100	
SOY	37	27-May-2014	0	MAF BNC cable shorted during burnout prior to this run - Erroneous MAF data resulting in erroneous ER calculations

Note: Cells highlighted in red indicate runs that were excluded from the dataset used for the steady-state analysis. These runs were also excluded from the multivariable regression analysis used to develop the model for predicting transient phase emission rates. However, the transient phase data for Run 24 were used to validate the model, as discussed later.

The complete dynamometer test cycle used to generate the data included a start-up phase, a warm-up phase, a transient phase mimicking real-world driving behavior, and three steady-state phases. The test cycle phases and operating conditions are described in detail in **Table 3-2** and **Figure 3-1**.

Table 3-2: Description of dynamometer test cycle

Dynamometer Test Cycle					
Phase Number	**Description**	**Duration**	**Rotational Speed (rpm)**	**Throttle width (%)**	**Average Nominal Load (%)**
0	Engine off	--	--	--	--
1	Idle	--	--	--	--
2	Warm up cycle	--	--	--	--
3	Transient cycle	60 min	--	--	12%
4	Transition to first steady state cycle	--	--	--	--
5	First steady state cycle	10 min	2700	35	5%
6	Transition to second steady state cycle	--	--	--	--
7	Second steady state cycle	10 min	2000	45	36%
8	Transition to third steady state cycle	--	--	--	--
9	Third steady state cycle	10 min	3000	60	50%
10	Idling of engine at end of run (transition back to phase 0, engine off)	--	--	--	--

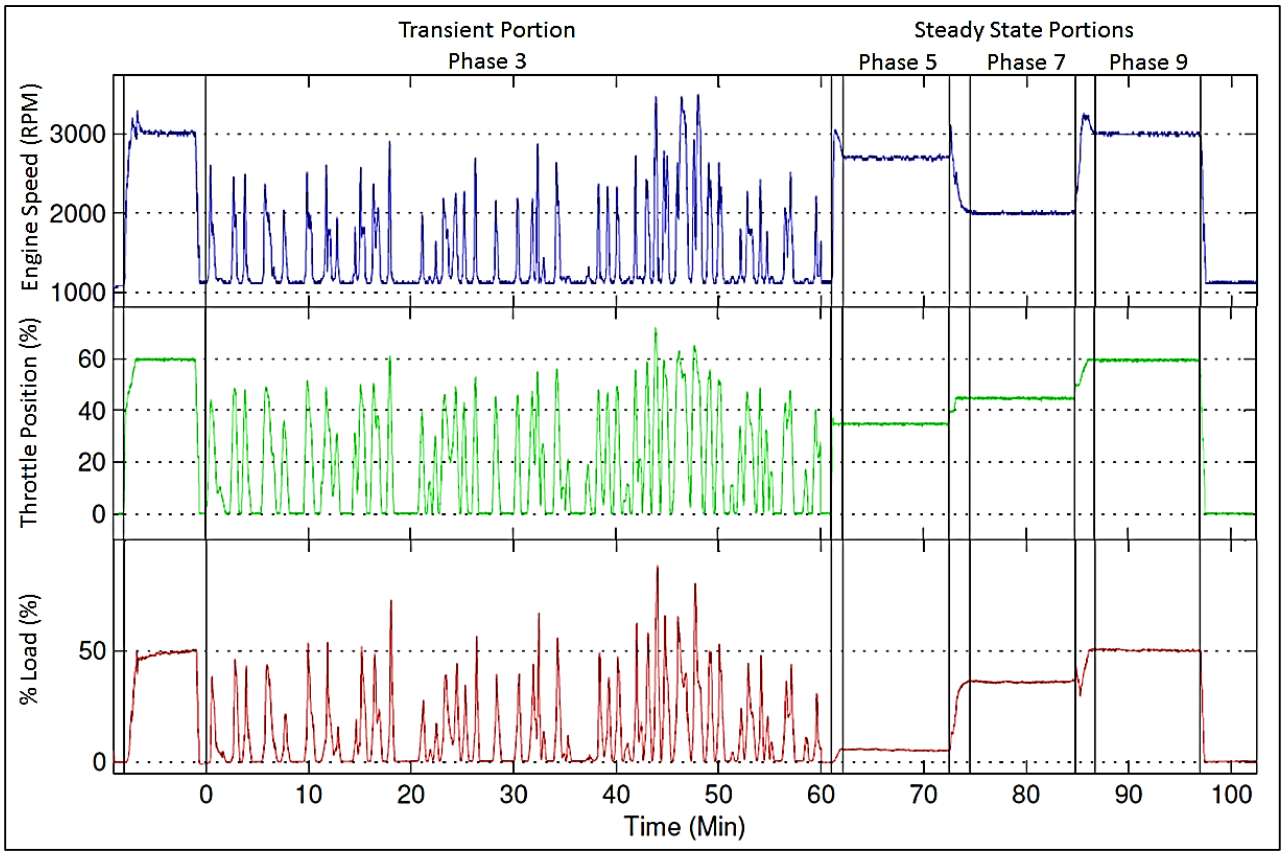

Figure 3-1: Engine and throttle positions throughout the course of the drive cycle (Feralio, 2015a)

The analysis conducted for this study focused on gas-phase emissions produced during the transient portion (Phase 3) and the steady state portions (Phases 5, 7, and 9) of the drive cycle. The transient portion was developed by using the speed-time trace of a 2003 Volkswagen TDi Jetta sedan with an automatic transmission as it was driven on real-world roads in downtown Burlington in Chittenden County, Vermont. The drive cycle was adjusted by approximately three seconds per one second of the real-world data collected in order for the CM-12 engine to handle the loads on the engine without stalling out. Each of the steady-state phases represents an increasing load setting. Thus Phase 5 simulates a low engine load, while Phase 9 is the highest load setting (see **Table 2-1**).

When collecting data, the run sequence involved instrument and background checks before and after the sampling run. Instrument blanks were run on each individual instrument to assess its behavior on a particular day and for a particular run, while also checking for potential contamination. With respect to the FTIR instrument, the instrument blank checked for the signal strength and the signal to noise ratio for each day. Tunnel blanks were measured by running the full data collection system, with all instruments connected and operating as they would during testing, but before the engine has been turned on. This provided information on the background measurement of the ambient conditions on a daily basis, as well as the day-to-day sensitivity of the instrument to trace amounts of the ambient gas species and contaminants. For instance, the tunnel blank data measured by the FTIR provided information on the humidity of each day (from the concentration of water in the air, measured as a percent) and the background level of CO_2 (measured as a percent) (Sentoff, 2015).

The data collection run sequence involved the following. First, the instrument blank measurements were taken, followed by the tunnel blanks. Next, the engine was turned on and allowed to warm up (as seen in the leftmost section of **Figure 3-1**). Once the engine had warmed up, the engine underwent the transient run schedule (Phase 3 in **Figure 3-1**), followed by the three 10-minute steady-state portions (Phases 5, 7, and 9 in **Figure 3-1**). Once the third and final steady-state phase had been completed, the engine was turned off, and then tunnel blank and instrument blank measurements were taken again (Sentoff, 2015).

3.2 Spectral Analysis

The exhaust emissions data (which were compiled into a database that was last updated on August 1, 2014) were collected using a MKS MultiGas 2030 High Speed Fourier Transform Infrared (FTIR) instrument, whose specifications are provided below in **Table 3-3**:

Table 3-3: Fourier Transform Infrared (FTIR) Spectrometer Specifications

Specification	**Description**
Manufacturer	MKS Instruments
Model	MultiGas 2030 High Speed
Infrared Source	Silicon Carbide @ 1200°C
Detector	Mercury Cadmium Telluride (Liquid Nitrogen Cooled)
Windows	Potassium Bromide
Path-Length	5.11 meters
Spectral Resolution	0.5 cm^{-1}
Scanning Rate	5 scans per second
Reference Laser	Helium Neon
Sample Temperature	191°C
Sample Handling	Particulate Filters on Inlet (2.0 µm and 0.1 µm pore-size)
Sample Flow Rate*	10+ liters per minute

**measured on a run-to-run basis*

Spectra were collected at 1-Hz temporal resolution, although there were occasional missing seconds of data caused by lagging of the hardware. The raw spectra had been previously processed with MKS MultiGas 2030 High Speed software (version 06.31.06) using a list of compounds (known as the *method*) that was compiled in April 2013, which included the compounds listed on the following page. Processing the spectra provided raw concentration measurements for each second for which an IR spectrum was collected. All concentrations were reported in ppm using calibration data collected at 191°C unless otherwise noted. For information on the spectral regions used for identification and quantification, see **Table A-1** in **Appendix A**.

List of compounds quantified using the April 2013 method:

- 1,2,4-Trimethylbenzene
- 1,3,5-Trimethylbenzene
- 2-Heptanone (150°C)
- 2-Pentanone (150°C)
- Acetaldehyde
- Acetone
- Acrolein
- Benzaldehyde
- Benzene
- Butyraldehyde
- CO (measured in ppm and as a %)
- CO_2 (%)
- Crotonaldehyde
- "Diesel" (unburned fuel)
- Ethyl benzene
- Ethylene *(quantified for soy biodiesel only)*
- Formaldehyde
- H_2O (%)
- Heptane (150°C)
- Hexane (150°C)
- *m*-Xylene
- N_2O (nitrous oxide)
- NH_3 (ammonia)
- NO_2 (nitrogen dioxide)
- NO (nitrogen oxide)
- *o*-Xylene
- Propanal (propionaldehyde)
- Styrene
- Toluene

Following processing of the spectra using the MKS MultiGas software, the raw concentration values were then reprocessed using a MATLAB code written by other members of the UVM TAQ Lab. The MATLAB code used a correction computed as the average background concentration from the pre-run tunnel blank, plus three times the standard deviation of the tunnel blank. This correction was calculated for every run, and thus each run used different background correction concentration values. This accounts for daily variation in ambient pollutant concentration and instrument behavior and sensitivity. Raw concentration values that fell below the background correction value were reported as zero.

Because the mass air flow (MAF) changed throughout the drive cycle due to changes in the engine speed, it was important to account for this by computing the emission rates of the pollutants instead of the concentration. The background corrected concentration values were used to calculate the emission rates using the following formula:

Equation 1

$$Emission\ Rate_i\left[{}^{mg}/_{\sec}\ or\ {}^{\mu g}/_{\sec}\right] = \frac{C_i\left[ppm\ or\ \%\right]\cdot MW_i\left[{}^{g}/_{mol}\right]\cdot Q_{TP}\left[{}^{L}/_{\min}\right]\cdot P_{FTIR}\left[atm\right]}{R\left[\frac{L\cdot atm}{mol\cdot K}\right]\cdot\left(T_{FTIR}\left[^{\circ}C\right]+273.15\right)\cdot 60\left[{}^{\sec}/_{\min}\right]}$$

where Emission Rate$_i$ = emission rate for gas analyte i in units of mg/s (for analytes measured in %) or μg/s (for analytes measured in ppm)
C_i = blank corrected concentration of gas analyte, i (% or ppm)
MW_i = molecular weight of analyte i
Q_{TP} = tailpipe flow rate at the point of sampling
P_{FTIR} = pressure of sample in sample cell
R = universal gas constant
T_{FTIR} = temperature of sample in sample cell (converted from °C to K)

3.3 Data Quality Checks

3.3.1 Detection Limit Check

Prior to data analysis, the concentration measurements were checked to confirm whether or not the compounds of interest had sufficient measurements to provide a reliable comparative analysis. As mentioned in the previous section, the raw measurements were corrected using the method detection limit, which was based on the tunnel blank measurements. **Table 3-4** shows the percent of raw measurements for CO, CO_2, formaldehyde, NO, and NO_2 that fell below the method detection limit. A full table (**Table A-2**) showing the percent of measurements below the detection limit for all compounds in the April 2013 method can be found in **Appendix A**.

Table 3-4: Percent (%) of measurements below the method detection limit for each compound by run

Run #	Bio%	Test Date	Run of Day	CO (ppm)	CO_2 (%)	Formaldehyde	NO	NO_2 *
1	B000	18JUN2013	1	3%	4%	3%	3%	3%
2	B000	25JUN2013	1	3%	4%	3%	3%	4%
3	B000	06AUG2013	1	2%	2%	2%	2%	2%
4	B010	29AUG2013	1	2%	2%	2%	2%	2%
5	B010	30AUG2013	1	1%	1%	1%	1%	1%
6	B010	31AUG2013	1	2%	2%	2%	2%	2%
7	B020	04SEP2013	1	3%	3%	3%	2%	2%
8	B020	05SEP2013	1	2%	2%	2%	2%	2%
9	B020	06SEP2013	1	2%	2%	2%	2%	2%
10	B050	09SEP2013	1	2%	2%	2%	2%	2%
11	B050	10SEP2013	1	1%	2%	2%	1%	1%
12	B050	11SEP2013	1	2%	2%	2%	2%	2%
13	B100	19SEP2013	1	2%	2%	2%	2%	2%
14	B100	20SEP2013	1	2%	3%	2%	2%	2%
15	B100	20SEP2013	2	4%	4%	4%	4%	4%
16	B000	22OCT2013	1	2%	2%	2%	2%	2%
17	B000	24OCT2013	1	2%	2%	2%	2%	2%
18	B000	25OCT2013	1	3%	3%	3%	3%	3%
19	B000	01MAY2014	1	3%	4%	3%	4%	4%
20	B000	02MAY2014	1	3%	3%	4%	4%	3%
21	B010	05MAY2014	1	2%	2%	2%	3%	2%
22	B010	06MAY2014	1	3%	3%	3%	4%	3%
23	B010	06MAY2014	2	2%	2%	2%	3%	2%
24	B020	07MAY2014	1	2%	3%	3%	4%	3%
25	B020	07MAY2014	2	2%	2%	2%	2%	2%
26	B020	12MAY2014	2	2%	2%	2%	2%	2%
27	B020	13MAY2014	1	3%	4%	17%	4%	3%
28	B020	13MAY2014	2	3%	3%	3%	4%	3%
29	B020	14MAY2014	1	3%	3%	3%	3%	3%
30	B020	15MAY2014	1	3%	3%	3%	3%	3%
31	B050	20MAY2014	1	3%	3%	4%	3%	3%
32	B050	20MAY2014	2	4%	4%	4%	4%	4%
33	B050	22MAY2014	1	8%	8%	8%	8%	8%
34	B100	23MAY2014	1	22%	27%	23%	28%	27%
35	B100	23MAY2014	2	4%	4%	4%	4%	4%
36	B100	26MAY2014	1	3%	3%	3%	3%	3%
37	B000	27MAY2014	1	3%	3%	3%	3%	3%

*Note: NO_2 can be quantified using two different calibration curves in the MKS database, one for the lower wavenumbers ("NO_2 low," ranging from 628 to 1753.49 cm^{-1}) and one for the higher wave numbers ("NO_2 high," ranging from 2763.78 to 2948.92 cm^{-1}). The concentrations quantified using "NO_2 low" were used in this analysis because a lower percent of the measurements fell below the detection limit (**Table A-2**).

3.3.2 Abnormal Run Data

Table 3-1 summarizes the data collection record taken by the members of the lab who conducted the test runs. Cells in red indicate run data in the dataset which were excluded from this thesis analysis. Runs without run numbers were previously excluded by the data collectors and were not included in the dataset provided to the analyst. Of the 37 runs in the dataset, three runs (Runs 24, 27, and 37) were excluded from the analysis based on abnormalities in the data, which were likely affected by experimental problems during data collection. For example, during the data collection for Run 24, the FTIR instrument experienced an error, resulting in no measurements being collected for the steady-state run phases (Phases 5, 7, and 9). Run 27 also had documented instrumentation problems during the data collection – a pump was not connected properly, which may have allowed ambient air to dilute the exhaust. The fact that gas concentrations measured for Run 27 were significantly lower than the measurements for any other run supports this possibility. Consequently, the Run 27 data was excluded from the analysis. Finally, the concentrations were measured correctly for Run 37, but the mass air flow (MAF) measurements, which were needed to compute pollutant emission rates (ERs), were all negative because a cable for the device measuring the air flow shorted out. Thus, Run 37 was also excluded from analysis.

3.4 Data Analysis Methods

A statistical analysis of the gaseous emissions data from the steady-state phases (Phases 5, 7, and 9) was conducted to study the effects of biodiesel feedstock (waste vegetable oil (WVO) versus soybean (SOY)), biodiesel fuel blend (B0, B10, B20, B50, or B100), and engine operating conditions on CO_2, CO, NO, NO_2, and formaldehyde. All statistical analyses were conducted using JMP 11 software. The findings of the statistical analysis were then used to produce a multivariate linear regression model to predict the emissions produced during the transient portion (Phase 3) of the drive cycle.

3.4.1 Steady-State Emissions Analysis

Two-way analysis of variance (ANOVA) tests were conducted on the emissions data for the three steady-state phases (Phases 5, 7, and 9) to determine whether or not the biodiesel feedstock (WVO vs. SOY), biodiesel fuel blend (Bio%), and the steady-state phase of the drive cycle each had a significant effect on the emission rates (µg/s) for the five pollutants. The full summary table of the ANOVA test results for each pollutant can be found in **Appendix B**, **Table B-1** through **Table B-5**. The two-way ANOVA tests were conducted in JMP 11, with each factor treated as a nominal variable. The ANOVA tests were set up as follows:

- For each biodiesel **feedstock** (WVO and SOY), the effects of the *fuel blend* and *drive cycle phase*, plus their interactive effect, were evaluated for the five pollutant emission rates;
- For each steady-state **phase** (Phases 5, 7, and 9), the effects of *feedstock* and *fuel blend* and the interaction between the two were tested; and
- For each biodiesel fuel **blend** (B0, B10, B20, B50, and B100), the effects of *feedstock* and *phase*, plus their interaction, were tested for significance.

The means tested in the statistical analyses were the arithmetic mean of around n=1800 samples. Each steady-state phase was around 10 minutes long. With data collected at 1-Hz temporal resolution, this amounts to approximately 600 measurements. In addition, each fuel blend was run in triplicate, which comes to a total of 1800 measurements for a single fuel blend. SOY B0 and SOY B20 blends were the only exceptions to having triplicate run data – SOY B0 has only duplicate data because one of the SOY B0 runs (Run 37) was eliminated (3.3 Data Quality Checks), while SOY B20 used data from five runs (**Table 3-1**). Some precaution needs to be taken with interpreting the statistical analyses when using such a large sample size. A larger sample size results in a more representative mean, but statistical tests will be more sensitive to small differences in the mean value.

3.4.2 Transient Phase Analysis

Using the JMP 11 "fit model" feature, a log-linear regression model was produced to predict the transient phase emission rates for each pollutant. Initially, a linear regression model was created for each feedstock and fuel blend, resulting in 10 models for each of the five pollutants. However, this approach posed several problems. Firstly, using a linear regression model was not suitable for the data because the emission rates were not normally distributed. Taking the natural logarithm of the emission rates helps produce a more normally-distributed dataset, as show below in **Figure 3-2**.

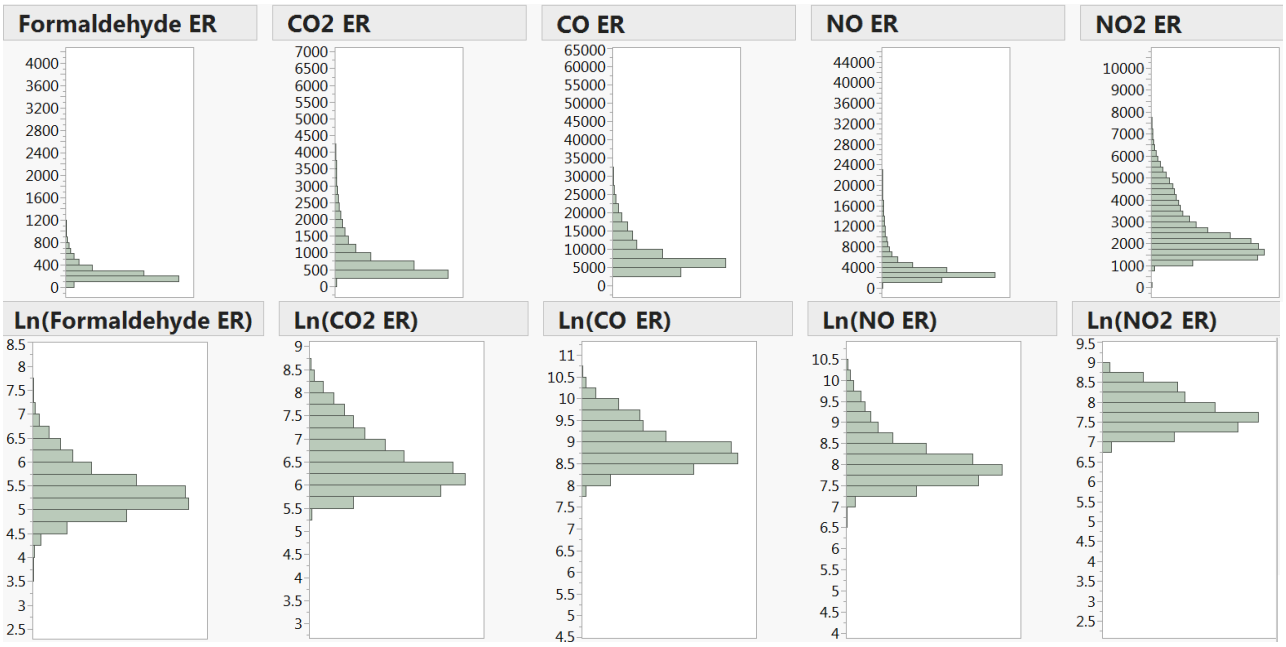

Figure 3-2: Distribution of emission rates and natural logarithm of the emission rates for each pollutant

The other advantage of using a log-linear model is that it forces the predicted values to be positive, which can provide more realistic predictions

4. Results and Discussion

4.1 Steady-State Analysis

The steady-state emissions analysis is presented below for each of the five pollutants (formaldehyde, CO_2, CO, NO, and NO_2). For each pollutant, the effects of phase, fuel blend, and biodiesel feedstock are discussed, including information provided by the statistical analyses and how the observed trends compare with the existing literature.

Overall, the ANOVA tests (**Appendix B**) showed that biodiesel feedstock, fuel blend, and the drive cycle phase each had a significant effect on the emission rates of all five pollutants, with the one exception of the effect of feedstock on B10 CO emission rates. (That is, the CO emission rates for B10 fuel blends were not statistically different when using WVO or SOY biodiesel.) In addition, comparison of the F ratios showed that phase consistently had a greater effect on emission rates for all five pollutants than either the feedstock or fuel blend, regardless of the fuel blend or feedstock used, except for B0 and B20 NO_2 emission rates. This suggests that the engine operating conditions was overall the greatest determining factor in pollutant generation.

In addition, pairwise student t-tests (**Appendix C**) were conducted to check whether the mean emission rates were significantly different, which helped confirm the two-way ANOVA results. Further discussion of the results of the ANOVA and t-test analyses are provided below for each pollutant.

4.1.1 Formaldehyde Emission Rates

Figure 4-1 shows the mean formaldehyde emission rates (µg/s) for biodiesel blends of both feedstocks, with the bars indicating each steady-state test phase.

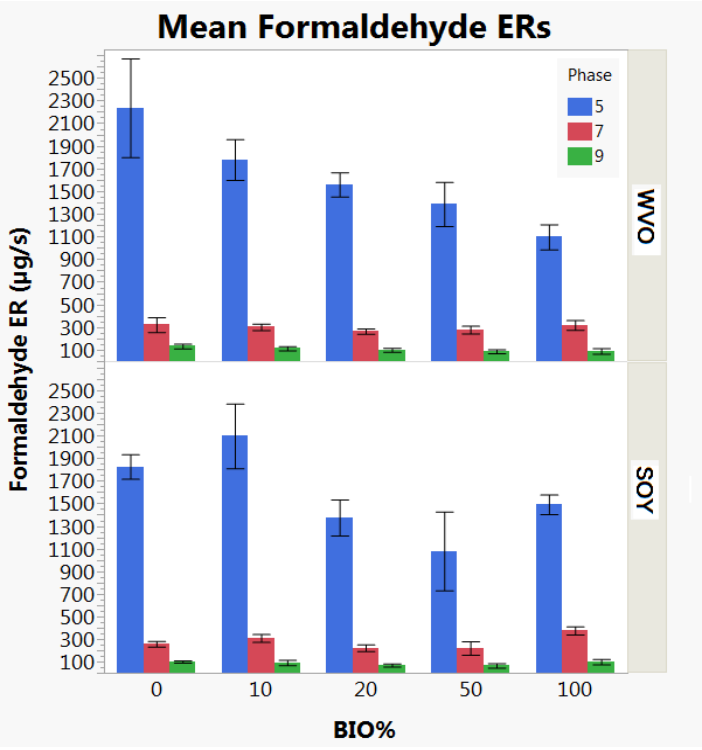

Figure 4-1: Mean formaldehyde emission rates. The error bars indicate one standard deviation above and below the mean.

Most of the existing research studies focusing on the effect of biodiesel use on formaldehyde and other carbonyl emissions report their findings either as a percent reduction from B0, as a percent normalized to B0, in units of mass of pollutant emitted per distance driven (such as mg/km), or as either a fuel-normalized or CO_2-normalized emission rate (ER) on a mass basis (mass of pollutant emitted per mass of fuel consumed, or mass of pollutant produced per mass of CO_2 emitted – CO_2 acts as a surrogate for fuel). To compare the magnitude of the measured formaldehyde ERs in this study with the existing literature, CO_2-normalized ERs were computed as follows:

Equation 2

$$ER\ (mg \cdot kg^{-1}\ CO_2) = \frac{ER\ (\mu g/s)}{CO_2\ ER\ (mg/s)} \cdot 1000 \frac{(mg \cdot kg^{-1}\ CO_2)}{(\mu g \cdot mg^{-1}\ CO_2)}$$

where ER ($mg \cdot kg^{-1}$ CO_2) = CO_2-normalized emission rate in units of $mg \cdot kg^{-1}$ CO_2
ER (µg/s) = ER as computed from Equation 1
CO_2 ER (mg/s) = ER as computed from Equation 1 for CO_2
1000 = conversion needed to convert $\mu g \cdot mg^{-1}$ CO_2 to $mg \cdot kg^{-1}$ CO_2

Table 4-1 below shows the CO_2-normalized formaldehyde ERs. Tables showing the CO_2-normalized ERs for formaldehyde, CO, NO, and NO_2 can also be found in **Appendix D**.

Table 4-1: Mean Formaldehyde CO_2-Normalized Emission Rates (mg/kg CO_2)

Effects of Bio% & Phase on WVO Emission Rates			
	Phase 5	**Phase 7**	**Phase 9**
B0	1707	170.5	30.71
B10	1324	157.2	25.29
B20	1161	133.0	21.89
B50	1077	137.8	19.37
B100	879.5	157.7	20.13
Effects of Bio% & Phase on SOY Emission Rates			
	Phase 5	**Phase 7**	**Phase 9**
B0	1946	183.9	32.03
B10	2162	210.4	27.19
B20	1385	145.8	20.39
B50	1106	143.7	20.15
B100	1309	204.7	24.81

These ERs can be compared to those obtained by a study conducted in 2012 by Magara-Gomez et al., which reported a range of CO_2-normalized ERs between 60-115 mg/kg CO_2. The CO_2-normalized ERs measured in this study covered a much larger range of values than those reported by Magara-Gomez et al. (2012). The Magara-Gomez et al. study used a 1993 John Deere agricultural tractor, which operated at only two different modes: idle for 10 minutes, followed by operations at 2100 rpm and 126.08 HP for 20 minutes. Both the tractor engine and the LDD engine used in this study did not use any after-treatment technology; both of these studies thus measured the engine-out emissions. One possible explanation for the difference in the range of ER values may be due to the greater variety of engine operating modes studied with the LDD engine than the tractor used in the Magara-Gomez et al. study.

Effect of phase on formaldehyde emissions

Formaldehyde emission rates consistently *decreased* with increasing run phase – that is, as the engine load increased, formaldehyde ERs decreased. This trend was consistent for each biodiesel blend and feedstock, and was also confirmed by the pairwise t-tests (**Table C-3**, **Appendix C**). This is consistent with findings in previous studies, which have also demonstrated a correlation between increasing engine load and a reduction in carbonyl emissions. Karavalakis et al. (2011b) showed that carbonyl emissions were higher for the New European Drive Cycle (NEDC) and the Artemis Urban cycles than the more aggressive (higher engine speed and load) Artemis Roadway and Artemis Motorway driving cycles. The reduction in carbonyl emissions experienced when driving at a higher engine speed and load was attributed to an increase in combustion efficiency due to higher engine temperatures. Other studies have also suggested that higher exhaust temperatures, which result from operating at a higher engine speed and load, also improves the performance of an oxidation catalyst, which would further reduce hydrocarbon (including carbonyl) emissions (Bikas and Zervas, 2007; Karavalakis et al., 2011b). However, the engine used in the TAQ Lab experiment did not have any pollution control or after-treatment devices (such as a catalyst), and thus the second explanation cannot account for the trends observed in this study.

Effect of fuel blend (Bio%) on formaldehyde emissions

The effect of fuel blend (*x*-axis in **Figure 4-1**) was less consistent across each phase or biodiesel feedstock. For WVO fuel blends (**Figure 4-1**, top), formaldehyde emissions produced during Phase 5 of the drive cycle consistently showed a reduction in the emission rate with increasing Bio%. All Phase 7 and 9 emissions showed a reduction in the formaldehyde emission rates for all biodiesel blends when compared to B0 (petrodiesel). However, the emission rates for B50 and B100 were sometimes greater than the B10, B20, or B50 emission rates – in other words, formaldehyde emission rates did not show linear reduction with increasing biodiesel fuel content.

Peng et al. (2012) suggested that volatile organic compounds (VOCs) may reflect varied responses to increasing biodiesel fuel content because the emissions produced are the net effect of two mechanisms. The first mechanism results in a reduction in VOCs due to the higher oxygen content in biodiesel fuel, which enhances combustion efficiency. The second mechanism results in an increase in VOCs because the additional oxygen found in biodiesel fuel could result in more oxygenated VOCs being produced. In other words, the two mechanisms that have been used to explain either an increase or reduction in carbonyl emissions in other studies may be simultaneously involved. Fuel blends that cause a reduction in VOC emissions may achieve a balance between the two mechanisms so as to optimize the benefits of improved combustion efficiency from oxygenated fuel without significantly increasing the risk of producing more oxygenated products of combustion. It is interesting to note that both the Peng et al. (2012) study, which used waste soybean oil biodiesel, and the soy biodiesel (SOY) data from this study both achieved the lowest emission rates with the B50 fuel blend.

Effect of biodiesel feedstock on formaldehyde emissions

For the pure WVO and SOY biodiesel fuels, the mean WVO B100 formaldehyde ERs (1100 µg/s for Phase 5, 320 µg/s for Phase 7, and 91 µg/s for Phase 9) were consistently lower than those for SOY (1500 µg/s for Phase 5, 380 µg/s for Phase 7, and 100 µg/s for Phase 9). However, the difference between feedstocks decreased with increasing phase. Further analysis of the chemical composition may help explain these observations.

Statistical tests

The graphs suggest that the drive cycle phase had the greatest effect on formaldehyde emission rates (ERs), especially between Phases 5 and 7. Comparing the F ratio produced by the two-way ANOVA tests (**Table B-1**, **Appendix B**) helped confirm that the drive cycle phase, and thus the percent engine load, had overall the greatest effect on the formaldehyde ERs. This can also be seen in the two-way tests comparing the effects of phase and feedstock for each of the five fuel blends, as well as the effects of phase and fuel blend for each of the two feedstocks. Fuel blend had a greater effect on formaldehyde ERs than feedstock for Phase 5 (low engine load) and Phase 7 (medium engine load), but the feedstock had a greater effect than the fuel blend for Phase 9 (high engine load).

4.1.2 Carbon Dioxide (CO_2) Emission Rates

Figure 4-2 below shows the emission rate trends for CO_2.

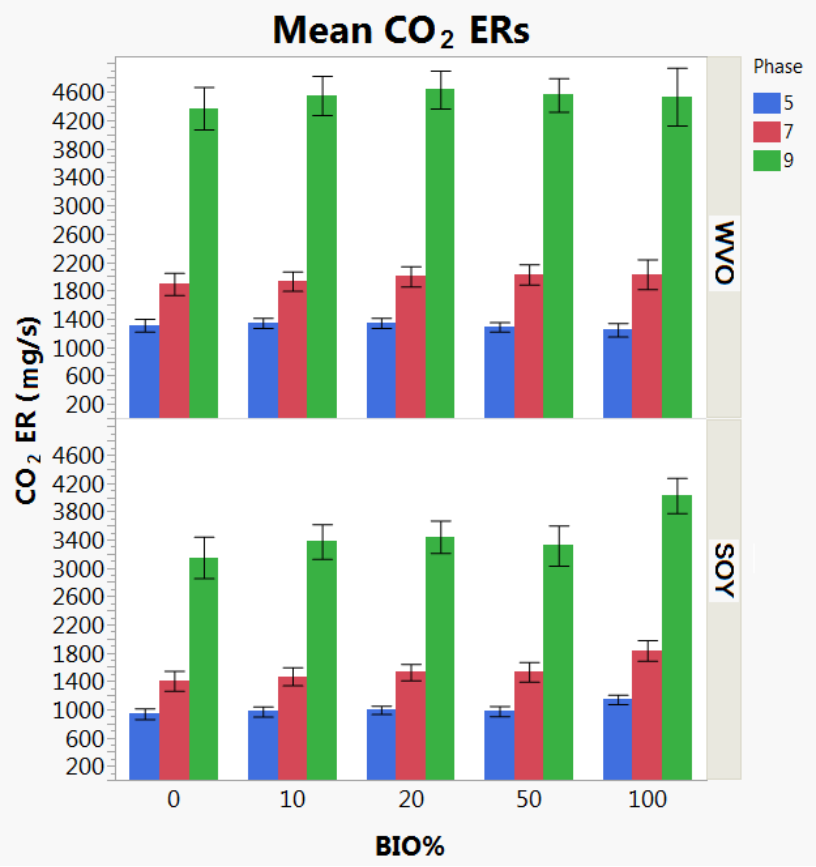

Figure 4-2: Mean CO_2 emission rates by fuel blend, phase, and biodiesel feedstock. The error bars indicate one standard deviation above and below the mean.

Effect of phase on CO_2 emissions

As shown in **Figure 4-2**, there is a clear relationship between the phase and CO_2 ERs. The mean CO_2 ER increased with phase for all fuel blends and for both feedstocks, which likely reflects an increase in fuel consumption with increased engine speed and load. This is to be expected, as driving at a higher speed or under a greater load requires greater power. Consequently, more fuel must be consumed to supply the energy required. With increased fuel consumption, more CO_2 will be produced. Thus, CO_2 emissions can be seen as reflection of the fuel economy of the vehicle (Karavalakis et al., 2009b, 2014).

Effect of fuel blend (Bio%) on CO_2 emissions

For the WVO biodiesel runs, almost all of the biodiesel blends produced slightly higher CO_2 emission rates than the petrodiesel runs. The only exceptions were the B50 and B100 blends during Phase 5 of the drive cycle, which actually produced slightly lower CO_2 ERs. All of the SOY biodiesel runs showed a statistically significant increase in CO_2 emission rates when using biodiesel blends when compared to the B0 CO_2 ERs. In general, CO_2 emission rates increased with biodiesel fuel content; however, a few of these increases did not test as being statistically significant ($p<0.05$) (**Table C-4** and **Table C-5**). Existing literature on CO_2 emissions from biodiesel use are somewhat limited because few older studies report CO_2 emissions, as it was not required to be measured in an emissions test. Of the studies that have investigated the effect of biodiesel use on CO_2 emissions, there is not much consensus among their findings, except that the effect of biodiesel use on tailpipe CO_2 emissions is fairly limited. Some studies have suggested that CO_2 emissions are sometimes slightly reduced, although not to a statistically significant degree (Karavalakis et al., 2009a, 2009b), while others reported a slight increase in CO_2 emissions. Kousoulidou et al. (2012) reported an increase in CO_2 emissions of up to 3% when using B100 biodiesel (an average taken from testing biodiesels derived from palm, waste-cooking, rapeseed, sunflower, and soy oils) in two 2004 Euro 3 diesel passenger cars driven on the New European Driving Cycle (NEDC).

In general, most studies that observe an increase in CO_2 emissions in the range of 3-6%, and attribute the increase in CO_2 emissions to an increase in fuel consumption (Karavalakis et al., 2011b; Kousoulidou et al., 2012; Turrio-Baldassarri et al., 2004), for both light-duty and heavy-duty diesel engines and vehicles. Karavalakis et al. (2011b) noted that the increase in fuel consumption was also greater for oxidized biodiesel fuels than the other biodiesel fuels. This increase in fuel consumption may result from a number of factors. Firstly, biodiesel has a lower H:C ratio than petrodiesel due to the presence of the carbonyl group, which replaces one of the H-C bonds. Consequently, more carbon is injected into the cylinder for the same energy content (Kousoulidou et al., 2012). In addition, most biodiesel fuels have a lower heating value than petrodiesel (around 12-14% lower [Lapuerta et al., 2008; Tat, 2003]), which means biodiesel fuel produces slightly less power than petrodiesel. As a result, a greater amount of fuel is required to make up for the loss in heating value (Lapuerta et al., 2008; Kousoulidou et al., 2012; Tat, 2003). In other words, a larger quantity of biofuel is injected to meet the required load. However, the difference in heating value between biodiesel and petrodiesel generally does not cause any significant loss in power unless the engine is operating at close to maximum power (Lapuerta et al., 2008). This may account for some of the differences in CO_2 trends observed between different studies using different engines operating at different loads or different drive cycles. Another factor that may cause an increase in fuel consumption (and thus CO_2 emissions) is related to the greater

viscosity of biodiesel compared to petrodiesel. Because biodiesel is more viscous, a greater mass and volume of fuel is injected into the combustion chamber (Lapuerta et al., 2008; Tat, 2003).

Effect of biodiesel feedstock on CO_2 emissions

For the CO_2 emission rates (ERs), all WVO blends consistently produced higher ERs than the SOY biodiesel blends. This may reflect differences in fuel consumption, which could result from differences in the fuel properties, especially viscosity, as previously discussed.

Statistical analysis

The two-way ANOVA tests revealed that the drive cycle phase had the greatest effect on CO_2 emissions, based on the higher F ratio associated with phase in comparison to the other two variables (**Table B-2**). In addition, the effect of the feedstock was consistently greater than the effect of fuel blend on CO_2 emissions, although the degree to which the feedstock had a greater effect decreased with increasing drive cycle phase.

4.1.3 Carbon Monoxide (CO) Emission Rates

Figure 4-3 below summarizes the emission rates observed for CO.

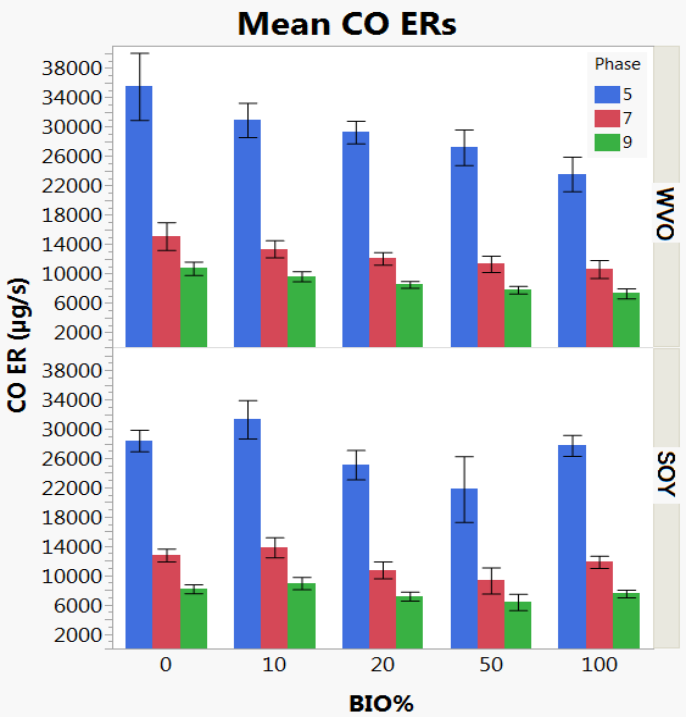

Figure 4-3: Mean CO emission rates by fuel blend, phase, and biodiesel feedstock. The error bars indicate one standard deviation above and below the mean.

Effect of phase on CO emissions

As shown in **Figure 4-3**, the CO ERs decreased with increasing phase across all fuel blends and for both feedstocks. This is consistent with the findings for formaldehyde (**Figure 4-1**) discussed above, suggesting that engine operating conditions had a similar effect on these two pollutants. At a higher engine load, higher in-cylinder temperatures can be achieved, which promotes better fuel evaporation and mixing of the air and fuel within the combustion chamber. This in turn leads to more complete combustion, and thus a reduction in products of incomplete combustion, such as CO (Roy et al., 2013).

Effect of fuel blend (Bio%) on CO emissions

For the WVO data, all biodiesel blends consistently produced lower CO ERs than B0, and the ERs decreased with increasing biodiesel fuel content. However, the trend was not as straightforward for the SOY emissions data. All of the B10 blends produced higher CO ERs than B0. From B10 to B50, the CO ERs decreased with increasing biodiesel fuel content, but all B100 CO ERs were greater than the B50 ERs for the same phase and feedstock. Thus the fuel blend containing a lower amount of SOY biodiesel produced higher CO ERs than the pure petrodiesel fuel, while the other fuel blends containing higher percentages of SOY biodiesel produced lower CO ERs. However, after a certain point (around B50), increasing the biodiesel fuel content did not further reduce the CO ER.

Roy et al. (2013) observed similar trends as those produced by the WVO biodiesel blends in this study, in which higher biodiesel fuel content produced a greater reduction in CO emissions. They also observed that the reduction in emissions was greatest for the lowest load setting (39% reduction for B100 at 3% load), and a slightly lesser reduction was experienced at the medium load setting (18% reduction for B100 at 48% load). However, at the highest load setting (96% load), the CO emissions produced by pure biodiesel was slightly greater than the B0 emissions by 5%. The study by Roy et al. thus suggested that the effectiveness of biodiesel blends in reducing CO emissions was diminished at high load settings. A table showing the percent reduction in emission rates relative to B0 as observed in this study is shown below in **Table 4-2**. In addition, the comparable percent reduction in CO ERs from the Roy et al. study are provided in the rightmost columns.

Table 4-2: Comparison of CO emission rate change (%) between B100 and B0 fuels

WVO - TAQ Lab (2013-2014)		SOY - TAQ Lab (2013-2014)		CANOLA - Roy et al. (2013)	
Ave. %Load	% change in ER (B100 vs. B0)	Ave. %Load	% change in ER (B100 vs. B0)	Ave. %Load	% change in ER (B100 vs. B0)
5	-34	5	-2.3	3	-39
36	-30	36	-7.3	--	--
50	-32	50	-8.1	48	-18
--	--	--	--	96	5

The decreasing trend in the effectiveness of replacing petrodiesel with pure biodiesel with increasing engine load was not observed in this study as it had been by Roy et al. The percent reduction in CO ERs resulting from replacing petrodiesel with WVO biodiesel was diminished very slightly with higher engine loads, but remained around 30%. The reduction in CO ERs produced by using SOY biodiesel actually increased with increasing engine load, but the overall percent reduction in CO ERs was much lower for the SOY biodiesel than those observed in the WVO dataset or from the canola biodiesel studied by Roy et al. This suggests that the combined effect of phase and fuel blend may vary by biodiesel feedstock, which means the chemical composition of the biodiesel fuel itself likely has an effect on CO emissions. Differences in the type of engine used (a Petter diesel engine, model PH2W, versus a Volkswagen 1.9L SDi industrial diesel engine) may have also affected the results.

Neither the measured data in this study nor observations made in previous studies can explain the anomalous increase in CO ERs experienced by the B10 blends. Most existing literature report either a reduction in CO emissions with the replacement of petrodiesel with biodiesel (Karavalakis

et al., 2009a, 2009b; Lapuerta et al., 2008; Roy et al., 2013), or no significant difference (Lapuerta et al., 2008; Turrio-Baldassarri et al., 2004). One study by Charlet et al. (1997) reported an increase in CO emissions of up to 60% when operating a heavy-duty engine in idle during the ECE R49 test cycle. But running the same engine on biodiesel during most of the other modes resulted in a reduction in CO emissions (Lapuerta et al., 2008).

The general justifications for the reduction in CO emissions with biodiesel fuel usually address the oxygenated nature of biodiesel. Many studies explain that the oxygen content in biodiesel fuel helps enhance a complete combustion of the fuel, which leads to a reduction in products of incomplete combustion such as CO (Lapuerta et al., 2008; Roy et al., 2013). Other studies have also suggested that the increased cetane number for biodiesel fuels may also reduce CO formation during combustion by decreasing the chance of fuel-rich zones formation (Lapuerta et al., 2008). Finally, advanced injection and combustion resulting from biodiesel use have also been reported to reduce CO emissions (Lapuerta et al., 2008). This effect of biodiesel use on engine mechanics is further discussed in Section 4.1.4 Oxides of Nitrogen (NO_x) (NO and NO_2) Emission Rates.

Effect of biodiesel feedstock on CO emissions

Comparison of the B100 emissions showed that the soybean (SOY) biodiesel produced significantly higher CO ERs than the WVO biodiesel (**Table C-9**, final three rows). However, the B0 fuels used for the WVO test runs produced significantly higher CO ERs than the SOY B0 runs (**Table C-9**). Thus, the petrodiesel used for the WVO runs produced more CO than the petrodiesel used in the SOY runs. Consequently, with the exception of the B10 and B100 fuel blends, the petrodiesel-biodiesel blends for the WVO runs appeared to have higher CO ERs, even though the neat SOY biodiesel actually generated higher CO ERs than the neat WVO biodiesel fuel. On the other hand, the B10 SOY ERs were higher during Phases 5 and 7 (low and medium engine load), and the B100 SOY runs consistently produced higher CO emission rates than the B100 WVO fuel. Thus the chemical characteristics of both the biodiesel and petrodiesel fuels most likely had an effect on CO production during combustion.

With respect to the effect of different biodiesel feedstocks on CO emissions, some studies have observed that the degree of saturation appears to affect the degree to which CO emissions are reduced. Karavalakis et al. (2009b) observed that palm-based biodiesel caused a greater decrease in CO emissions than rapeseed biodiesel when using blends of B5, B10, and B20 on a 1998 Toyota Corolla 2.0 TD operating on the New European Driving Cycle (NEDC) and Athens Driving Cycle (ADC). This led to the observation that CO emissions appeared to decrease as the saturation level of the fuel was increased (Karavalakis et al., 2009b). An increase in saturation level also corresponds to a higher cetane number (Karavalakis et al., 2009b), which is another property that is commonly evaluated for diesel and biodiesel fuels.

Statistical analysis

The two-way ANOVA analysis revealed that of the three variables studied, phase (and thus engine operating conditions) had the greatest effect on CO emission rates, regardless of fuel blend and biodiesel feedstock. In addition, when comparing the strength of the effect of fuel blend and feedstock on CO emissions, for Phases 5 and 7 the fuel blend had the greater effect. However, under high load conditions (Phase 9), feedstock had a stronger effect on the emissions than the fuel blend. This pattern was also reflected in the formaldehyde emissions, and the similarity in the

behavior of these two emissions may be due to the fact that both pollutants are largely produced as a result of incomplete combustion.

4.1.4 Oxides of Nitrogen (NO_x) (NO and NO_2) Emission Rates

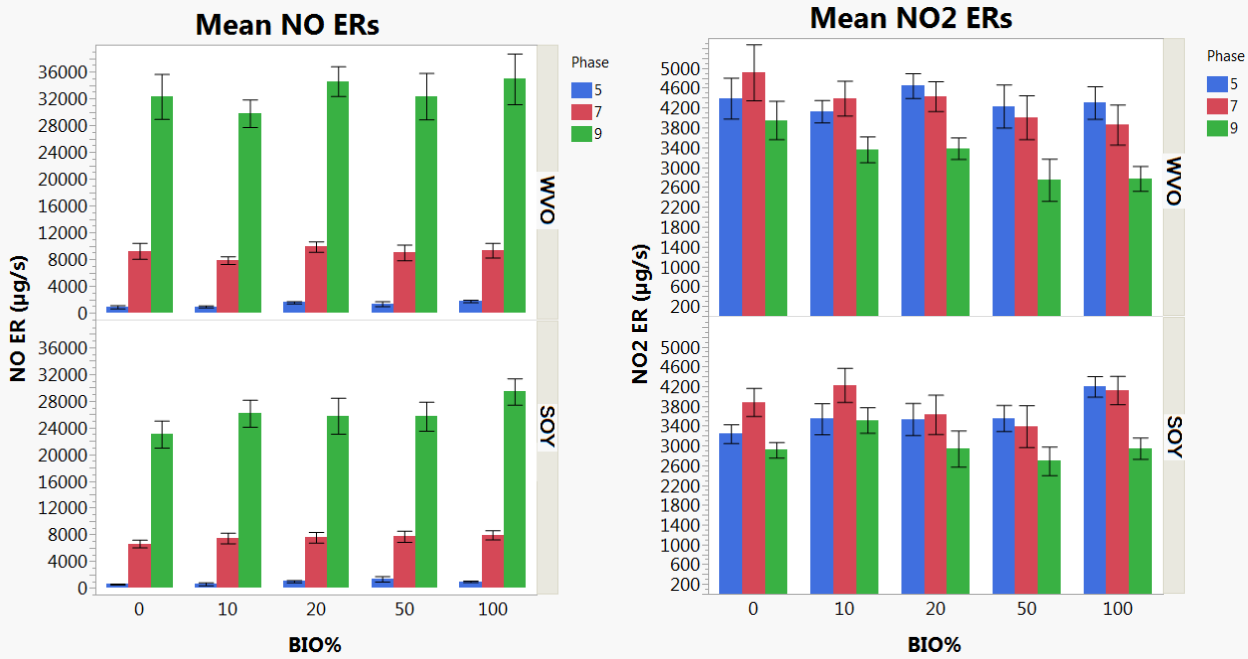

Figure 4-4: NO and NO_2 mean emission rates by feedstock, phase, and fuel blend. Error bars represent one standard deviation from the mean.

The statistical analyses suggested that phase, fuel blend, and feedstock each had a significant effect on both NO and NO_2 emissions. Phase generally had the strongest effect, as seen in the larger F ratios from the two-way ANOVA analysis. However, the trends for the NO_x pollutants were less straightforward than for the other exhaust emissions in this study.

Effect of fuel blend (Bio%) on NO_x emissions

For both WVO and SOY biodiesel fuels, NO emission rates (ERs) generally increased when using biodiesel fuel blends, compared to B0. For WVO, B10 NO ERs showed a reduction or no significant change compared to those for B0, while NO ERs exhibited a sharp increase for B20 WVO blends. NO ERs decreased when increasing the biodiesel blend from B20 to B50 for WVO, while B100 blends showed an increase in NO ERs compared to B50. NO_2 followed a very similar trend as NO for each fuel type.

According to Tat (2003), biodiesel has a higher speed of sound, which results in a faster propagation of pressure waves, as well as a greater bulk modulus, which promotes more rapid pressure rise. These two characteristics may cause combustion to occur earlier within the combustion chamber, which in turn may cause higher combustion temperatures and pressures. These conditions tend to result in increased NO_x formation, which may explain any increase in NO_x emissions with biodiesel use. However, Tat also noted that a shorter ignition delay tends to also decrease premixed combustion, which typically reduces NO_x formation. The resulting increase or decrease in NO_x formation depends on which of these factors is dominant, which depends on the situation.

Effect of phase on NO_x emissions

For NO, the increasing the engine load (an increase in phase number) consistently resulted in an increase in emission rates for both WVO and SOY biodiesel. An increase in engine load, and thus combustion temperature, is frequently associated with increased NO_x emissions (Lapuerta et al., 2008). Interestingly enough, NO_2 did not show a consistent increasing or decreasing trend with respect to phase. The effect of phase had a much less prominent effect on NO_2 than it did for NO. For both WVO and SOY, NO_2 emissions increased when changing from a low engine load (Phase 5, 5% load) to a medium load (Phase 7, 36% load) when using B0 or B10. This was also true for B20 blends of SOY biodiesel. However, for B20, B50, and B100 WVO blends, and B50 and B100 SOY blends, increasing the percent load caused a reduction in NO_2 emissions.

The change in the effect of phase (engine operating conditions, or engine load) for NO_2 with increasing biodiesel fuel content may be a result of a shift in NO/NO_2 equilibrium. As discussed further in detail in the next section, certain characteristics of biodiesel may lend it to having a shorter combustion delay than petroleum diesel. Consequently, the engine temperature can reach higher levels during combustion, which lends itself to increased NO_x formation. In engine combustion, usually NO is formed by the oxidation of atmospheric nitrogen (N_2). The following pair of equations was proposed by Zeldovich et al. (1947) as a mechanism describing how NO is formed. Firstly, free oxygen atoms (O) are produced in flames, either by dissociation of O_2 or by radical attack on O_2. These free oxygen atoms then attack nitrogen molecules and cause the following chain mechanism to take place (Flagan and Seinfeld, 1988):

$$N_2 + O \leftrightarrow NO + N$$

$$N + O_2 \leftrightarrow NO + O$$

This mechanism is highly endothermic, which means a large amount of heat is required for NO formation to take place (Flagan and Seinfeld, 1988). Thus, higher combustion temperature is closely associated with increased NO formation.

Usually, NO is later converted to NO_2 in the atmosphere; that is, NO_2 is not primarily produced as a direct result of combustion within the engine. The overall reaction for the formation of NO_2 from NO and atmospheric oxygen (O_2) is shown below (Flagan and Seinfeld, 1988):

$$NO + NO + O_2 \leftrightarrow 2NO_2$$

This reaction is thermodynamically favored at low temperatures, and occurs much more slowly than NO formation (Flagan and Seinfeld, 1988). Consequently, it would make sense that at higher engine load, where the combustion and exhaust temperatures would be higher, NO_2 formation would be reduced. This would likely explain the decrease in NO_2 emissions when increasing from medium to high engine load (Phase 7 to Phase 9). For fuel blends containing a higher biodiesel content, the oxygenated nature of the fuel, plus its higher speed of sound and bulk modulus, may cause sufficient elevation in combustion temperature to cause a net reduction in NO_2 formation. However, for fuel blends with a lower biodiesel fuel content, the increase in NO production may have overwhelmed the effect of increased combustion temperature, and thus caused an increase rather than a reduction in NO_2 formation.

Effect of biodiesel feedstock on NO_x emissions

For NO, WVO biodiesel consistently produced higher ERs than the SOY biodiesel blends, and in only one case (Phase 5, B50) the difference was not statistically significant. For NO_2, WVO biodiesel also produced higher ERs than SOY, with the exception of Phase 9, B10; Phase 7, B100; and Phase 9, B100 fuel blends.

Other studies have suggested that certain fuel chemistry properties, such as cetane number and saturation, can cause varying trends in NO_x emissions between biodiesels derived from different feedstocks. For instance, a study by Karavalakis et al. (2009b) studied blends of rapeseed methyl ester (RME) biodiesel and palm methyl ester (PME) biodiesel. RME NO_x emissions were found to be slightly higher than B0 NO_x emissions (although these differences were not statistically significant), while PME NO_x emissions were reduced by 10.9% to 12.06% for B5 and B10 blends of PME biodiesel, respectively. The justification for the difference in NO_x emissions behavior between these two biodiesel fuels was based on differences in fuel chemistry. PME has a higher cetane number than RME, which is often correlated to a shorter ignition delay period (Karavalakis et al., 2009b; Lapuerta et al., 2008). Once again, a shorter ignition delay means higher combustion temperatures can be achieved, which tends to increase NO_x production.

Such observations in fuel chemistry differences were not as immediately observable in this study because the two biodiesel fuels had very similar fatty acid methyl ester (FAMEs) profiles (Kasumba, 2014). Because the B0 (petrodiesel) fuels used for WVO had consistently produced higher emissions than the B0 fuels used in the SOY runs, the higher WVO emissions may have been a result of differences in the petroleum diesel blended with the biodiesel rather than differences in the fuel chemistry of the two biodiesel feedstocks.

4.2 Transient Phase Emissions Modeling

Following the analysis of emission trends in the steady-state phases of the drive cycle, an attempt to produce a log-linear regression model to predict emissions produced in the transient phase was conducted. From the results of the steady-state emission rate analysis, it was clear that the drive cycle phase had the greatest effect on the emission rates. "Phase" was used as a surrogate for the engine operating conditions, which includes factors such as the engine speed, engine load, and exhaust temperature. These three factors were used as independent variables for the transient engine operation emissions model. In addition, because the biodiesel fuel blend (Bio%) also had a significant effect on emissions, it was included as the fourth factor in the emissions model.

In the process of developing emission rate prediction models, the modeling approach started at a more refined scale by producing a model for each biodiesel feedstock and fuel blend, resulting in 10 models using three variables (percent engine load, engine speed, and exhaust temperature) for each of the five pollutants. The results of this modeling approach are presented in the **Appendix** in **Table E-1**. In addition, this model was a linear regression model, rather than a log-linear model. One major problem with using a linear regression model was that it could produce negative predicted emission rate (ER) values, which are unrealistic. A log-linear approach was thus taken instead, which involved using the natural logarithm of the measured ERs and fitting a multivariate function to these values instead.

To reduce the number of models required and improve the utility of the model, biodiesel fuel content (Bio%) became used as a variable in the model, reducing the number of models for each pollutant from 10 by a factor of five (because five fuel blends were used in this study). This also allowed the model to predict emissions for any biodiesel fuel blend. The resulting pair of log-linear models for each pollutant (one model for each biodiesel feedstock) were then compared. The parameters did not differ substantially between the two feedstocks, and thus it was determined appropriate to combine both models into a single model for each pollutant. The resulting model for each pollutant is presented in **Table 4-3**, which includes the model parameters for each of the five pollutants and the R^2 value.

Table 4-3: Model parameters for predicting transient phase emissions

	Pollutant:	Formaldehyde	CO_2	CO	NO	NO_2
	R^2:	0.279	0.802	0.477	0.738	0.543
Intercept	Estimate	4.53	5.10	7.86	7.07	6.91
	Std Error	6.39E-03	4.04E-03	5.21E-03	4.46E-03	4.43E-03
	t Ratio	708.88	1262.24	1508.24	1583.88	1559.72
	Prob > |t|	<.0001	<.0001	<.0001	<.0001	<.0001
%Load	Estimate	-1.39E-02	1.51E-02	-4.23E-03	2.17E-02	3.51E-03
	Std Error	1.18E-04	7.46E-05	9.61E-05	8.23E-05	8.17E-05
	t Ratio	-118.28	202.52	-44.05	263.44	42.94
	Prob > |t|	<.0001	<.0001	<.0001	<.0001	<.0001
Corrected Engine Speed (rpm)	Estimate	8.36E-04	6.96E-04	8.12E-04	3.50E-04	6.09E-04
	Std Error	4.02E-06	2.54E-06	3.27E-06	2.80E-06	2.78E-06
	t Ratio	208.31	274.02	248.06	124.77	218.77
	Prob > |t|	<.0001	<.0001	<.0001	<.0001	<.0001
Exhaust Temp (°C)	Estimate	-1.76E-03	2.12E-03	-8.47E-05	3.07E-03	-3.90E-04
	Std Error	5.39E-05	3.41E-05	4.39E-05	3.76E-05	3.74E-05
	t Ratio	-32.66	62.02	-1.93	81.47	-10.45
	Prob > |t|	<.0001	<.0001	0.054	<.0001	<.0001
Bio%	Estimate	1.03E-03	5.70E-04	-1.15E-03	-1.12E-03	-4.90E-04
	Std Error	3.61E-05	2.29E-05	2.95E-05	2.52E-05	2.50E-05
	t Ratio	28.52	24.93	-39.07	-44.34	-19.55
	Prob > |t|	<.0001	<.0001	<.0001	<.0001	<.0001

Note: The R^2 values displayed in this table describe how well the models fit the data used to produce the models.

Based on the R^2 values, the CO_2 model ($R^2 = 0.802$) could fit the data the best, while NO, NO_2, and CO could be modeled moderately well. However, the model produced for formaldehyde has a relatively low R^2 value, suggesting that the model may predict the formaldehyde emissions to the same degree of accuracy as the models for the other four pollutants.

To validate each model, the transient data for Run 24 was used to produce predicted second-by-second ERs for each pollutant, and then the predicted values were plotted against the measured values. Run 24 was one of the three runs excluded from the statistical analyses, including the log-linear regression analysis, because it was missing steady-state phase data. However, it still had usable transient phase (Phase 3) data, which made it suitable for use to check how well the models could predict the transient phase emissions. **Figure 4-5** below illustrates the input data on percent engine load (% Load [%]), engine speed (Corrected Engine Speed [RPM]), and exhaust temperature (Exhaust Temp [C]) from the transient portion of the Run 24 data. Run 24 tested a B20 blend of the SOY biodiesel (**Table 3-1**). The elapsed run time (*x*-axis) is measured in seconds for all plots.

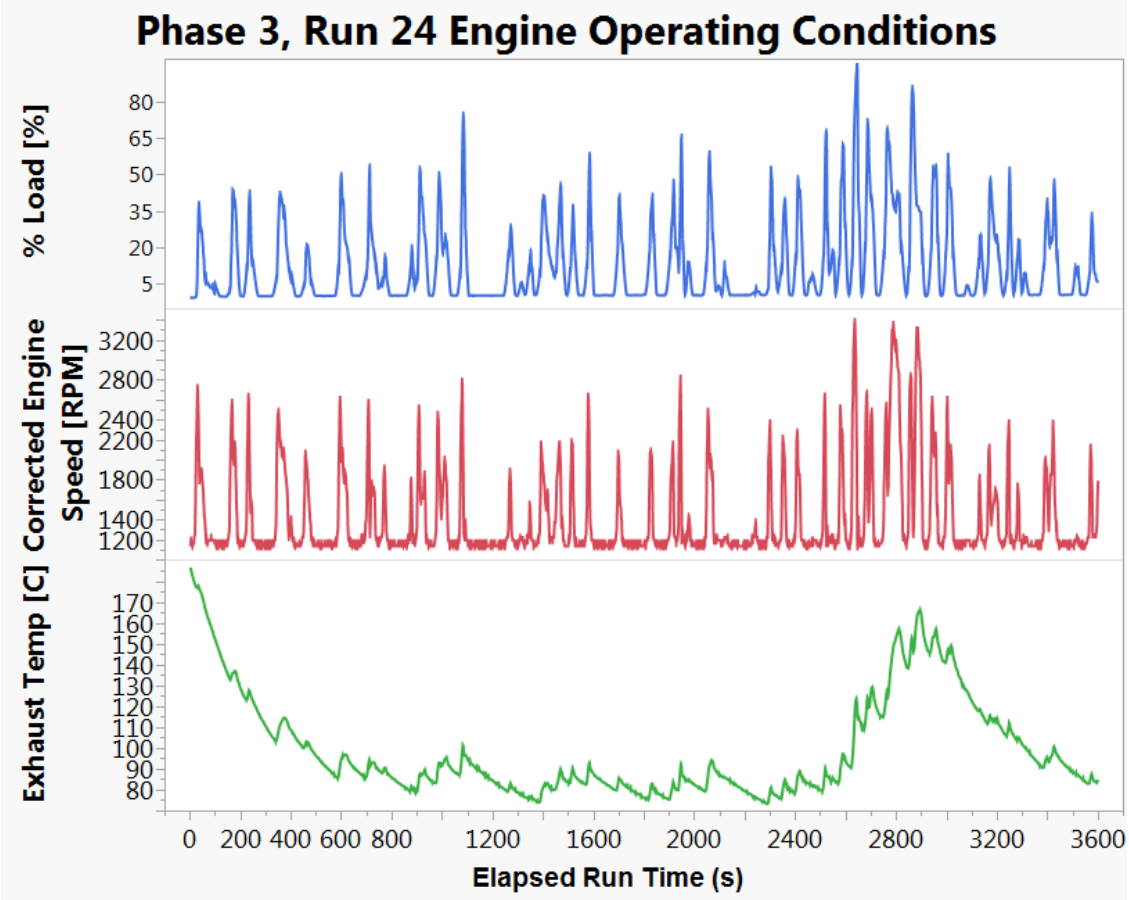

Figure 4-5: Transient phase second-by-second engine operating parameters from Run 24 used to validate the log-linear emissions models

Note on corrected engine speed: The engine speed was measured using two independent instruments. One instrument reported engine speed through the engine start and engine off periods, but its measurements were not aligned with the other, more robust instrument. Thus, the measurements from the first instrument were "corrected" in order to align it with the speeds reported by the more reliable instrument (Feralio, 2015b).

An important feature to note in **Figure 4-5** is the spike in exhaust temp between 2600 and 3300 seconds into the transient portion of the drive cycle. This part of the drive cycle was recorded while the vehicle was climbing uphill (recall that the transient portion of the drive cycle used the engine

speeds and throttle positions logged by a vehicle as it was driving through downtown Burlington, VT), which would account for the extreme engine conditions experienced during this portion of the run. In addition, the exhaust temperature at the beginning of the transient portion appears to be somewhat high as well, compared to the exhaust temperatures recorded during other parts of the run with the same engine speed and percent load. This may have been a result of the engine still being very warm after starting up and idling at high load and engine speed (as seen in the leftmost portion of **Figure 3-1**).

Each model was run using the second-by-second engine operating conditions data (percent engine load, corrected engine speed, and exhaust temperature) and the biodiesel fuel content (20%) for Run 24 as input values to produce the predicted natural log value of the ERs for every second of the transient cycle. These values were then used to calculate the second-by-second ERs by using the exponential function, as described in **Equation 3**:

Equation 3

$$ER_{predicted} = e^{[\ln(ER)]_{predicted}}$$

where $ER_{predicted}$ = predicted ER (µg/s for formaldehyde, CO, NO, and NO_2, mg/s for CO_2)
$[\ln(ER)]_{predicted}$ = predicted natural log value of the ER, as calculated using the log-linear emissions model

Every set of predicted and measured ER values were plotted against each other to determine the R^2 value (goodness of fit statistic) for each model. The R^2 values are summarized in **Table 4-4**:

Table 4-4: Summary of goodness-of-fit statistic of predicted emission rate (ER) values when validating each emissions model using Run 24 parameters as input

Pollutant	**R^2 value (goodness of fit)**
Formaldehyde	0.155
Carbon Dioxide (CO_2)	0.841
Carbon Monoxide (CO)	0.327
Nitrogen Oxide (NO)	0.831
Nitrogen Dioxide (NO_2)	0.529

4.2.1 Formaldehyde Emissions Model

Figure 4-6 shows the predicted (red) and measured (blue) formaldehyde ERs for the transient portion of Run 24.

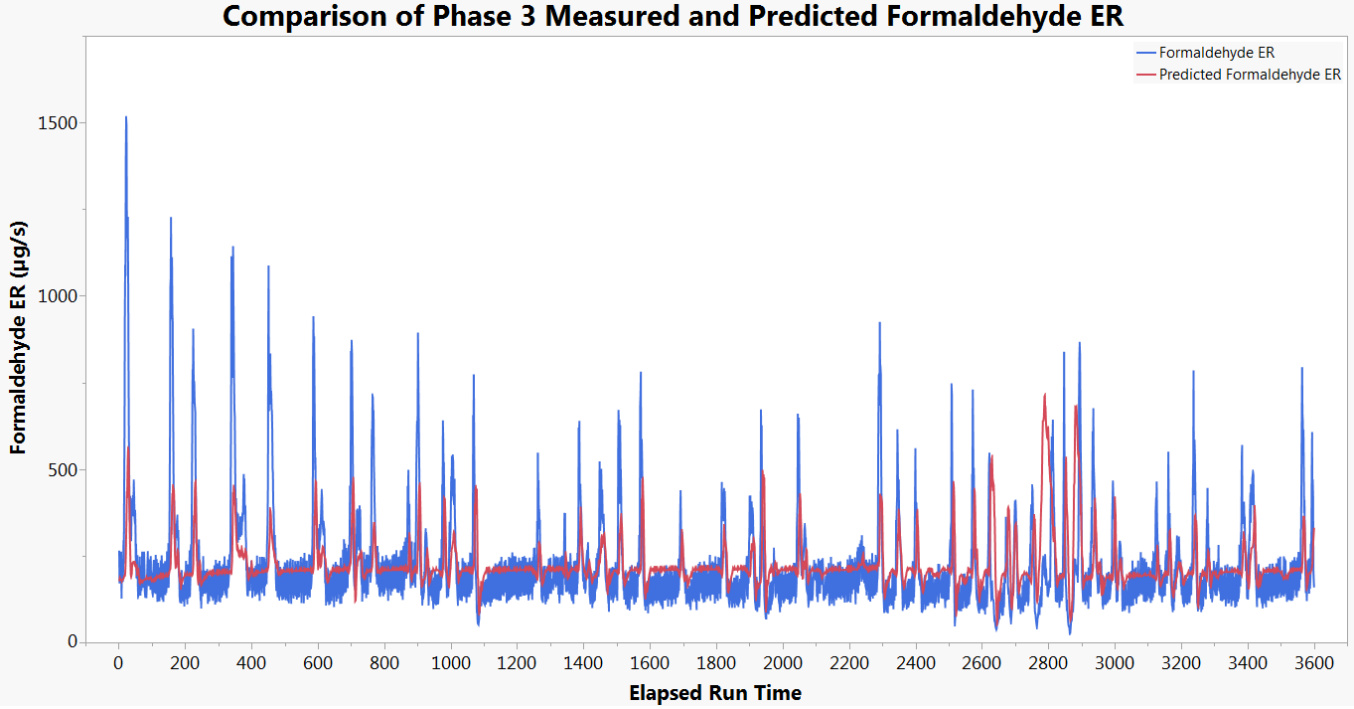

Figure 4-6: Predicted and measured formaldehyde emission rates over the time duration of the Run 24 transient phase

As seen in **Figure 4-6**, the modeled ERs (red) followed similar patterns as those shown by the actual, measured ERs (blue). However, the model struggled with predicting the extreme peaks in formaldehyde ERs for much of the transient portion of the run. Between 2600 and 2900 seconds of the run, the model at times over-predicted the formaldehyde ERs. This time frame corresponds to the part of the drive cycle that simulated more aggressive driving for driving uphill, which resulted in much higher exhaust temperatures (**Figure 4-5**). If a higher exhaust temperature was achieved, then it implies that the combustion conditions were more suitable for complete combustion. Consequently, it would be expected that formaldehyde, a product of incomplete combustion, would be emitted in lower amounts. Thus the actual behavior of the formaldehyde ERs, as seen in the measured data, is as expected. However, the model was not quite able to predict the reduction in formaldehyde ERs for this part of the transient run cycle.

The corresponding predicted versus measured formaldehyde ER plot (**Figure 4-7**) also reflects the problems that the model encountered with matching the high formaldehyde ER peaks. At higher measured formaldehyde ER values, the predicted ER value falls well below the 1:1 line (in blue), which indicates that the model underestimated the peak ER values.

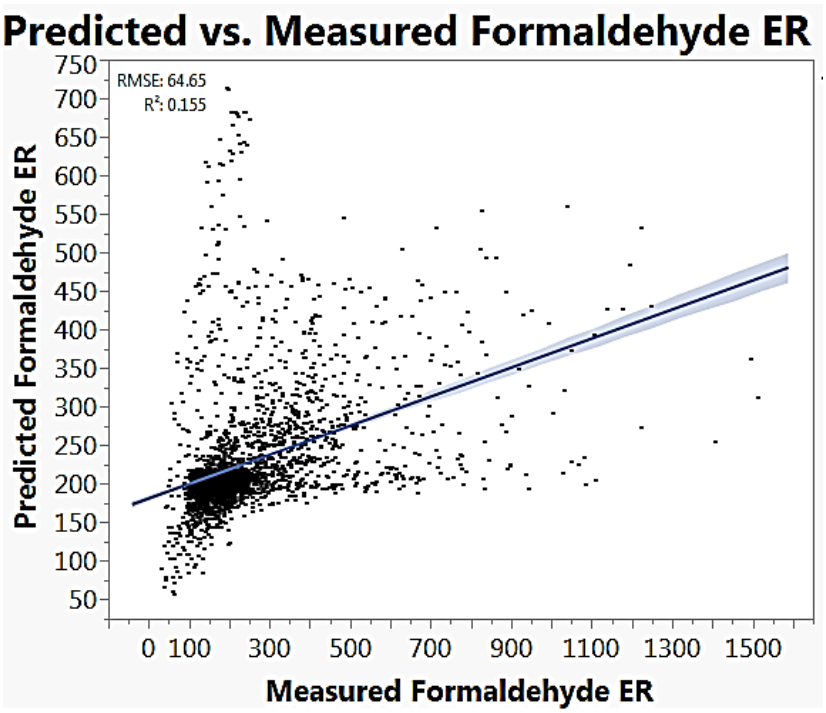

Figure 4-7: Predicted versus measured formaldehyde ER plot, used to determine the goodness-of-fit statistic, R^2. The blue shaded region indicates the 90% confidence interval.

Overall, it appears that the model may have actually fit the measured data fairly well, except for a few points where it overestimated the formaldehyde emissions to be around 450-725 µg/s where the actual measured emission rates were much lower, about 100-200 µg/s (left side, **Figure 4-7**). This most likely occurred during the high exhaust temperature event between 2600 and 2900 seconds, which produced a lower formaldehyde ERs than anticipated by the model, as seen in **Figure 4-6**. Because the peaks in formaldehyde ERs was much lower during this part of the drive cycle, it may have affected the model such that it underestimated the other formaldehyde ER peaks. In other words, the model may be trying to compensate for the unusually low formaldehyde ERs experienced during the high exhaust temperature event, which would cause its estimates for the high formaldehyde ER events to be lower than the actual formaldehyde ERs. One method to avoid this problem could be to produce a separate model to simulate aggressive driving behavior.

4.2.2 Carbon Dioxide (CO_2) Emissions Model

Carbon dioxide, on the other hand, could be predicted to a fairly high degree, as shown below in **Figure 4-8**:

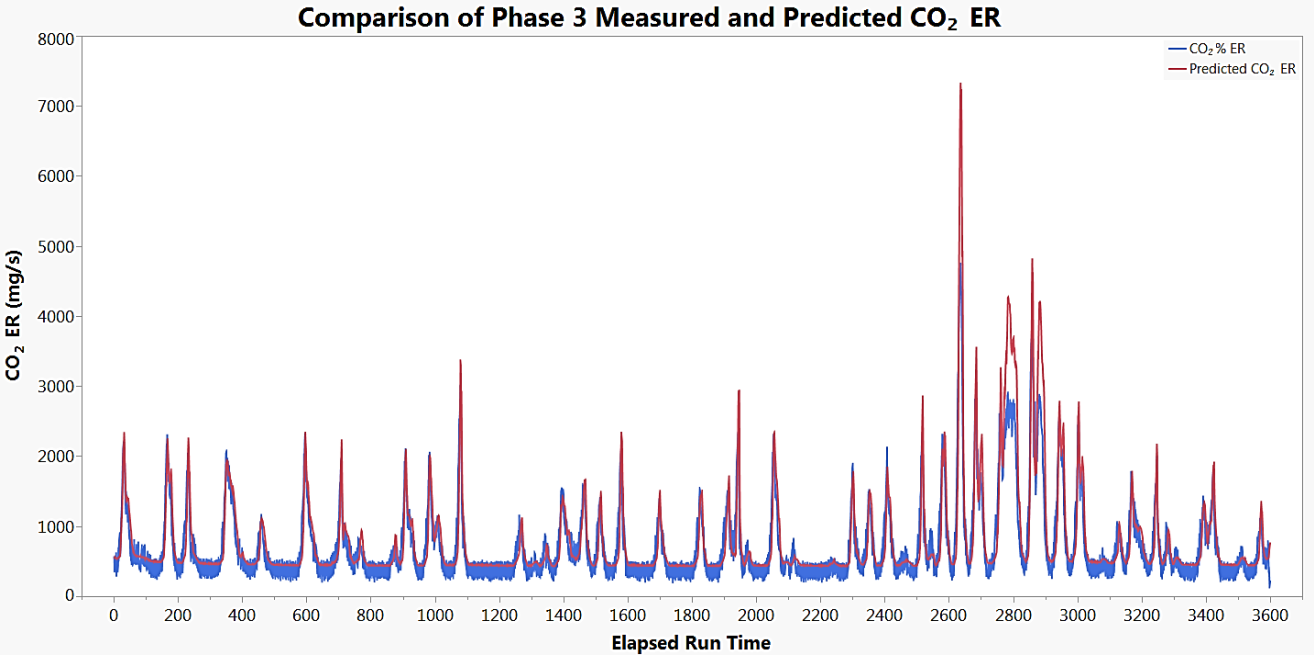

Figure 4-8: Predicted and measured CO_2 emission rates over the time duration of the Run 24 transient phase

Not only did the model (red) fit the pattern of peaks and valleys reflected in the measured CO_2 ERs (blue), but the predicted values were very close to the actual values. The model had some problems with the 2600-3000 second range – the aggressive portion of the transient phase for which the formaldehyde model had trouble predicting ER values. **Figure 4-9** (below) shows the predicted versus measured CO_2 ER plot.

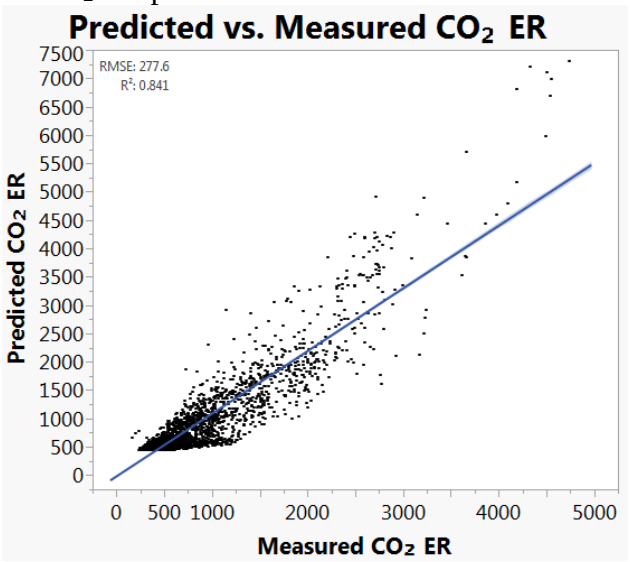

Figure 4-9: Predicted versus measured CO_2 ER plot, used to determine the goodness-of-fit statistic, R^2. The blue shading indicates the 90% confidence interval.

Based on the predicted vs. measured plot (**Figure 4-9**), the CO_2 model overall did a fairly decent job of predicting the CO_2 emission rates throughout the course of the transient portion, although it

overestimated a few of the ERs at the highest peaks, especially during the high exhaust temperature peak from 2600-3200 seconds of the transient cycle. In general, however, the predicted versus measured plot follows the 1:1 line (blue, **Figure 4-9**) quite well.

4.2.3 Carbon Monoxide Emissions Model

The CO model showed a moderately good fit, as shown below.

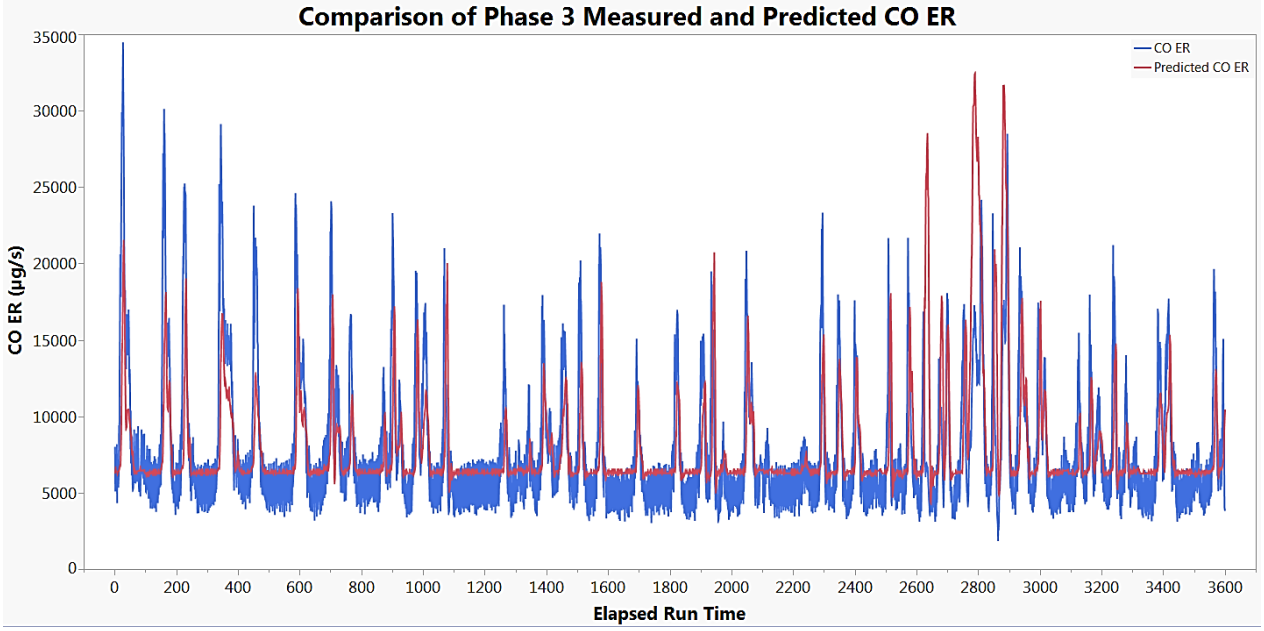

Figure 4-10: Predicted and measured CO emission rates over the time duration of the Run 24 transient phase

As seen in **Figure 4-10**, the predicted values followed the same trend in peaks and valleys of ERs, but it underestimated most of the high peaks in ERs, except around 2500-3000 seconds into the transient drive cycle, where some of the peaks were overestimated. Thus, the high exhaust temperatures experienced at this part of the transient cycle may have reduced the actual CO emissions much more than the model had anticipated.

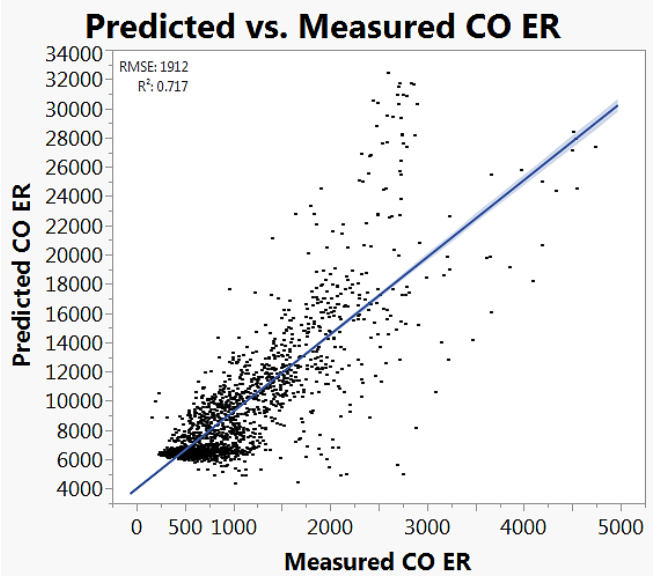

Figure 4-11: Predicted versus measured CO ER plot, used to determine the goodness-of-fit statistic, R^2. The blue shading indicates the 90% confidence interval.

The predicted versus measured CO ER plot (**Figure 4-11**) shows far more scatter than for any of the other models; there was more error associated with the estimates, and across a wide range of actual, measured CO ERs, not specific to a very particular range of CO ERs. To improve the model, it may be necessary to produce different models for different engine modes of operation, as suggested for formaldehyde. Consideration of other variables that may affect CO formation during combustion may also help produce a more accurate emissions model. Compared to formaldehyde and CO_2, part of the difficulty in modeling CO ERs lay in the significantly larger range of values that needed to be modeled. However, the NO ER model (discussed in detail in the following section) also had a similar range in ER values, but could be predicted accurately to a much higher degree. This shows that the range itself is not entirely to blame – it is possible to produce a model that can predict such a range of ER values fairly accurately, or at the very least, more accurately than the CO emissions model had. However, for CO it may require using additional or different input parameters other than the ones used in this model.

4.2.4 Nitrogen Oxide (NO) Emissions Model

The NO emissions could be modeled fairly well using the log-linear model, as shown below in **Figure 4-12**:

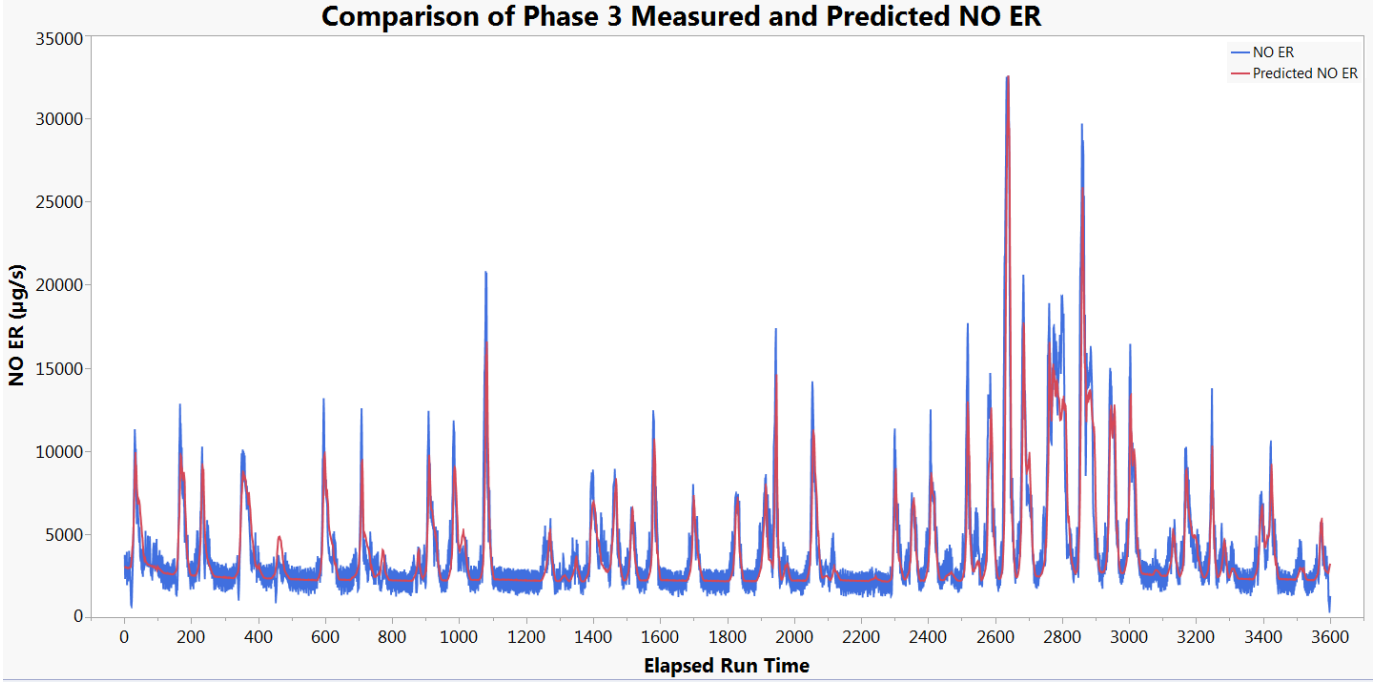

Figure 4-12: Predicted and measured NO emission rates over the time duration of the Run 24 transient phase

For the most part, the predicted NO ERs fit the pattern of the measured NO ERs quite well, even during the high exhaust temperature event between 2500-3000 seconds that the models for formaldehyde, CO_2, and CO had more difficulty with fitting. The predicted versus measured NO ER plot (**Figure 4-13**) also shows that overall the NO emissions model was able to predict the measured ERs very well.

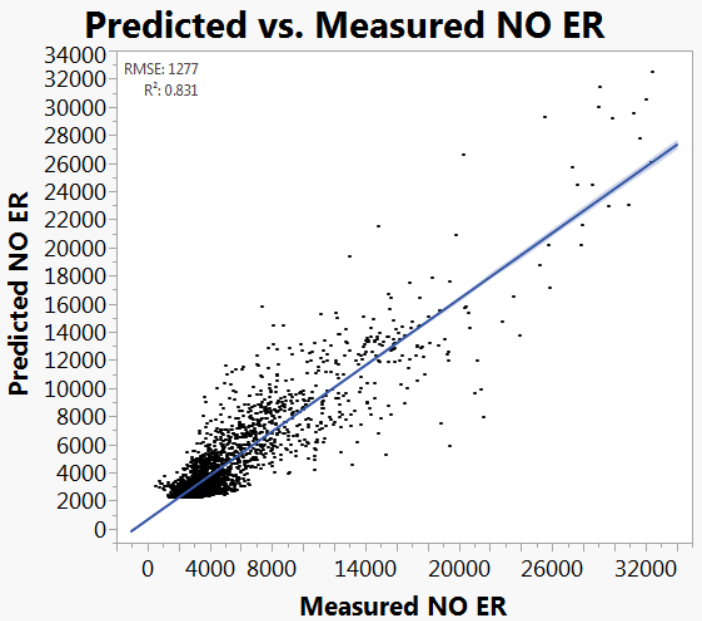

Figure 4-13: Predicted versus measured NO ER plot, used to determine the goodness-of-fit statistic, R^2. The blue shading indicates the 90% confidence interval.

As seen in **Figure 4-13**, while the range of NO ERs was comparable to that of the CO ERs, it appears that the majority of the ER values were still relatively low (less than 16,000 µg/s). Even so, the peak ER values still fell fairly closely along the 1:1 line (blue, **Figure 4-13**). This suggests that NO formation may be largely dictated by the engine operating conditions (percent engine load, engine speed, and exhaust temperature), as well as the biodiesel fuel content. This applied even when the engine was simulating more extreme conditions from uphill driving, which had caused problems with predicting the emissions for formaldehyde, CO, and CO_2.

4.2.5 Nitrogen Dioxide (NO_2) Emissions Model

The NO_2 model (**Figure 4-14**) could predict the emissions to a moderate degree of accuracy, exhibiting similar strengths and weaknesses as the CO ER model.

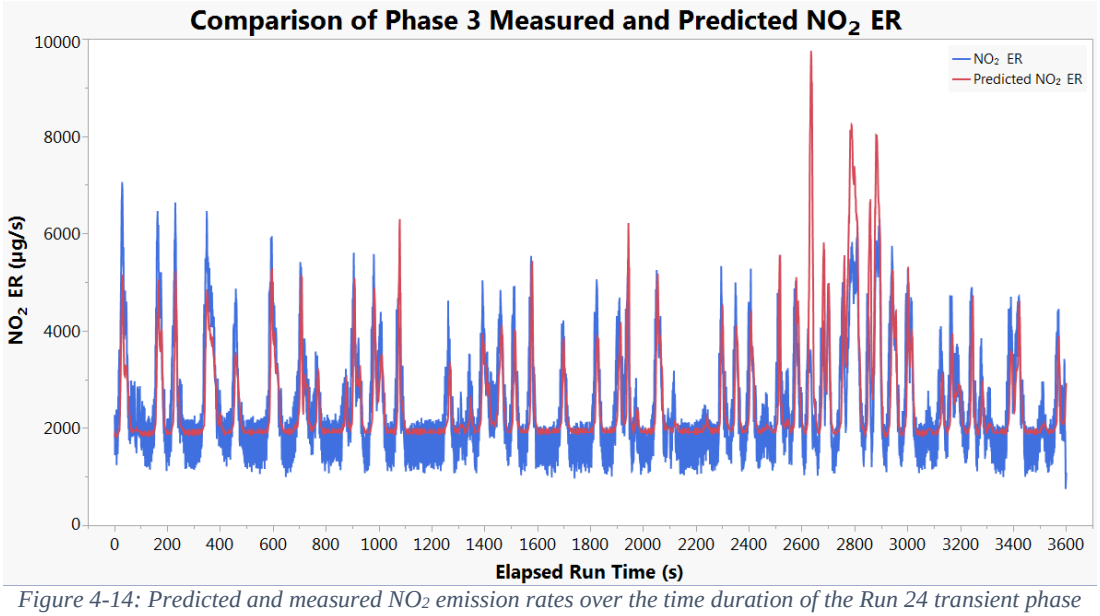

Figure 4-14: Predicted and measured NO_2 emission rates over the time duration of the Run 24 transient phase

Like the other models, the NO_2 model was able to reflect the same trend in peaks and valleys as the measured data. The model had trouble with the high exhaust temperature event between 2500-3000 seconds; some peaks in particular were greatly overestimated. Most peaks in other parts of the transient cycle were underestimated, but there were a few that had also been significantly overestimated. **Figure 4-15** (below) plots the model estimates ("predicted NO_2 ER") against the measured NO_2 ER values to determine the goodness of fit for the model:

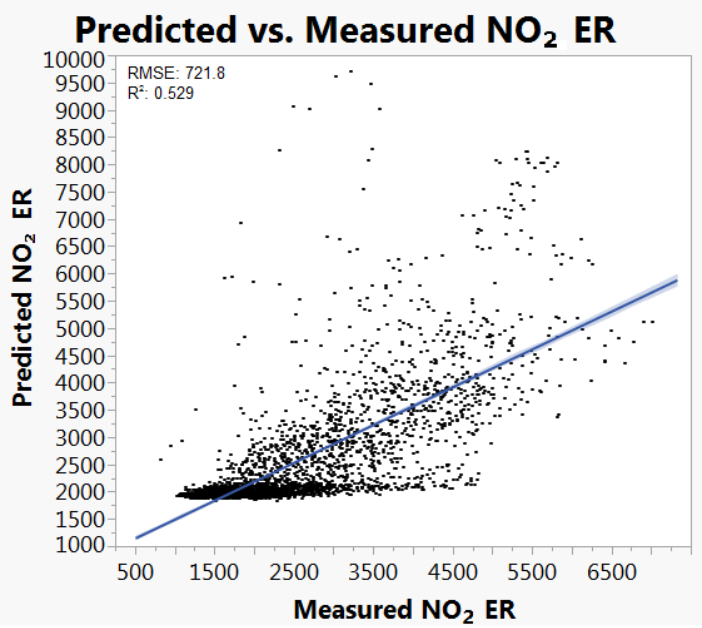

Figure 4-15: Predicted versus measured NO_2 ER plot, used to determine the goodness-of-fit statistic, R^2. The blue shading indicates the 90% confidence interval.

The dark, wide spread of points at the bottom left of Figure **4-15** shows that for low ER values, the actual measured NO_2 ERs covered a much wider spread of values than the model had predicted. This suggests that there may be additional factors in addition to the three engine operating parameters and biodiesel fuel content that would help provide more accurate estimates of the NO_2 emissions. It may be necessary, for instance, to consider the amount of NO that was produced, or the ratio of NO to NO_2 and its relationship to certain parameters that may affect the equilibrium between these two species, such as exhaust temperature, in order to produce a more accurate model.

5. Conclusions

The steady-state phase analysis determined that biodiesel fuel content, biodiesel feedstock, and "phase" (or engine load), each had a significant effect on formaldehyde, CO_2, CO, NO, and NO_2 emission rates (ERs). In addition, the effects of each of these factors on formaldehyde and CO were found to be quite similar, which may be due to the fact that formaldehyde and CO are both largely produced from fuel combustion as a result of incomplete combustion.

For formaldehyde and carbon monoxide (CO), increasing engine load (which, in the drive cycle used, was represented by increasing phase number, progressing from Phase 5 to Phase 7, and then to Phase 9) produced a reduction in formaldehyde and CO ERs. This supports previous findings, which have suggested that increasing engine load and speed reduce carbonyl and CO emissions

because the higher exhaust temperatures and improved fuel-air mixing resulting under these engine operating conditions enhance more complete combustion, which in turn reduces the creation of products of incomplete combustion. In general, increasing biodiesel fuel content (Bio%) reduced both CO and formaldehyde ERs. The higher oxygen content, higher speed of sound, and greater bulk modulus of biodiesel fuel may help promote more complete combustion (Tat, 2003), which would reduce the formation of products of incomplete combustion. Biodiesel feedstock also had a significant effect on both CO and formaldehyde emissions. The ERs for both CO and formaldehyde were consistently higher for the SOY B100 biodiesel than the B100 WVO biodiesel.

For carbon dioxide (CO_2), increasing the engine load produced higher CO_2 emission rates due to increased fuel consumption when demanding more power output from the engine. In addition, increasing the biodiesel fuel content caused a slight increase in CO_2 ERs, which may be a result of an increase in fuel consumption due to either physical and/or chemical properties of biodiesel fuel. Finally, all WVO fuel blends produced significantly higher CO_2 ERs than the corresponding SOY biodiesel fuel blends under the same engine operating conditions. These differences between the biodiesel feedstocks likely reflect differences in the chemical properties of both the petrodiesel and biodiesel fuels.

The trends for NO_x emissions were slightly more complex. Increasing engine load consistently produced higher NO emission rates for all fuel blends, and regardless of biodiesel feedstock. This most likely occurred because operating under higher engine load and speed results in higher exhaust temperatures, which produces more favorable conditions for NO formation. NO_2 formation appears to be affected by a combination of engine load and biodiesel fuel content. For fuel blends containing a lower amount of biodiesel (20% or less biodiesel), NO_2 emission rates were found to increase when changing the engine load from 5% to 36%, but further increasing the load from 36% to 50% resulted in a decrease in NO_2 emission rates. With fuel blends containing higher amounts of biodiesel, increasing the load only reduced NO_2 ERs. In addition, the amount of biodiesel in the fuel blend at which the effect of increasing load on NO_2 ERs switches from an increase to a reduction in ER values was different between biodiesel feedstocks.

The emission rate models produced in the second part of this study helped provide some insight on which variables can be used to predict emissions produced by real-world driving behavior. The log-linear models used percent engine load (%), engine speed (rpm), exhaust temperature (^oC), and biodiesel fuel content (%) as input parameters to predict the emissions for formaldehyde, CO, CO_2, NO, and NO_2. Each of these factors were shown to act as significant predictors of formaldehyde, CO, CO_2, NO, and NO_2 emissions. The models were then validated using the second-by-second transient engine operating conditions data for a test run whose data had been excluded from the regression analysis used to produce the models. Each model estimate was capable of reflecting similar patterns as the measured ER data. However, each pollutant model reflected a different degree of accuracy with respect to how closely the magnitude of the predicted emission rate values fit the measured emission rates. The CO_2 and NO models exhibited the best fits ($R^2 = 0.841$ and $R^2 = 0.831$, respectively). Formaldehyde and carbon monoxide each had the lowest goodness-of-fit (R^2) values (0.155 and 0.327, respectively), which suggests that additional factors likely affect the production of pollutants formed during incomplete combustion. The NO_2 model could predict ER values moderately well ($R^2 = 0.529$), but exhibited more error in predicting peak ER values under the more extreme engine conditions in the transient drive cycle. Because

NO emissions may affect NO_2 formation, further study of whether or not NO and NO_2 ERs are correlated may help produce a more accurate NO_2 emissions model. It may also be necessary to produce different models to account for differences in engine operating behavior, especially during more aggressive engine operation because each factor may affect pollutant formation differently under different types of engine operating conditions.

The findings of this study thus help contribute to understanding the relationships between biodiesel use and MSAT and criteria pollutant exhaust emissions from a light-duty diesel engine. The application of FTIR spectroscopy for quantifying gaseous emissions may also demonstrate the potential power in collecting emissions data at a high temporal resolution, which could provide more information on the relationships between engine conditions during transient or real-world operation and exhaust emissions. In addition, use of high-resolution data could provide a strong foundation for emissions models that could account for factors such as differences in engine operating conditions and biodiesel fuel content. Additional studies on exhaust emissions from other vehicle/engine types or using other drive cycle schedules would continue to further develop an understanding of how certain factors affect exhaust emissions with biodiesel use. In addition, the data provided from additional studies would provide more information which may be useful for emissions modeling under a greater variety of engine/fuel types and driving conditions. The literature review also revealed that studies on MSAT emissions from biodiesel fuel blends, especially for light-duty diesel engines, seldom report emissions data in consistent units between studies, which renders quantitative comparisons difficult. Without the use of comparable units, interpretation of the findings between studies is limited to a qualitative analysis of the trends and patterns observed in the data. Employing a consistent standard unit for reporting exhaust emissions data, such as mass of pollutant produced per unit mass of fuel consumed, would allow for direct comparisons between studies.

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A. Appendix A – Pollutant Quantification Details

Table A-1: List of compounds (April 2013 method) and the spectral regions used for quantification

Compound Name	**Compound calibration file name in MKS database**	**Analysis regions (cm^{-1})**
1,2,4-Trimethylbenzene	1,2,4-Trimethylbenzene 191c	800.32 – 833.35 (Region 00) 499.96 – 800.08 (Region 01) 833.59 – 1987.55 (Region 02) 2562.96 – 2991.57 (Region 03) 2991.81 – 3224.43 (Region 04) 3971.96 – 4499.65 (Region 05)
1,3,5-Trimethylbenzene	1,3,5-Trimethylbenzene 191c	826.36 – 863.38 (Region 00) 499.96 – 826.12 (Region 01) 863.72 – 1987.55 (Region 02) 2562.96 – 2991.57 (Region 03) 2991.81 – 3224.43 (Region 04) 3971.96 – 4499.65 (Region 05)
2-Heptanone	2-Heptanone low 150c	2740.15 – 3032.55 (Region 00) 499.96 – 631.82 (Region 01) 698.60 – 1191.08 (Region 02) 1191.08 – 1836.41 (Region 03) 3032.79 – 3229.98 (Region 04)
2-Pentanone	2-Pentanone 150c	2276.79 – 3048.70 (Region 00) 553.96 – 1502.54 (Region 01) 1656.82 – 1811.58 (Region 02) 2616.48 – 2776.55 (Region 03) 3048.95 – 3177.91 (Region 04) 3384.50 – 3504.07 (Region 05)
Acetaldehyde	Acetaldehyde 191C	2576.47 – 2863.57 (Region 00) 813.10 – 1915.23 (Region 01) 2863.81 – 3664.13 (Region 02)
Acetone	Acetone 191c	1150.59 – 1255.21 (Region 00) 499.96 – 613.98 (Region 01) 708.24 – 1150.35 (Region 02) 1255.45 – 1409.97 (Region 03) 1491.45 – 1856.42 (Region 04) 2726.65 – 3158.87 (Region 05)
Acrolein	Acrolein 191c	2851.05 – 2909.61 (Region 00) 606.51 – 2094.10 (Region 01) 2909.85 – 3133.80 (Region 02) 3363.29 – 3464.54 (Region 03)
Benzaldehyde (butanal)	Benzaldehyde 191c	2622.77 – 2899.03 (Region 00) 590.61 – 878.44 (Region 01) 963.77 – 1123.84 (Region 02) 1147.46 – 1491.46 (Region 03) 1564.50 – 1799.06 (Region 04) 3003.17 – 3143.95 (Region 05)
Benzene	Benzene 191c	3020.02 – 3125.36 (Region 00) 595.90 – 830.46 (Region 01) 963.76 – 1113.22 (Region 02) 1161.19 – 1531.12 (Region 03) 1720.94 – 2051.43 (Region 04) 2179.44 – 2430.14 (Region 05)

		2547.30 – 2686.15 (Region 06) 2771.24 – 2958.07 (Region 07) 2990.61 – 3019.78 (Region 08) 3125.61 – 3145.37 (Region 09) 4008.37 – 4141.68 (Region 10) 2509.54 – 4738.79 (Region 11)
Butyraldehyde	Butyraldehyde 191c	2584.66 – 3128.50 (Region 00) 499.96 – 1529.05 (Region 01) 1582.33 – 1955.49 (Region 02)
Carbon monoxide (CO)	CO ppm 191C (1of2)	2146.16 – 2159.90 (Region 00)
	CO% 191C (2of2)	2024.67 – 2039.13 (Region 00) 1929.69 – 2024.43 (Region 01) 2039.37 – 2146.16 (Region 02) 2159.90 – 2287.18 (Region 03) 3986.90 – 4381.52 (Region 04)
Carbon dioxide (CO_2)	CO2% 191C	2028.53 – 2131.46 (Region 00) 500.44 – 1181.44 (Region 01) 1819.77 – 2028.29 (Region 02) 2131.70 – 2525.35 (Region 03) 3271.68 – 3852.87 (Region 04)
Crotonaldehyde	Crotonaldehyde 191c	2648.78 – 2906.96 (Region 00) 499.96 – 579.99 (Region 01) 702.69 – 782.49 (Region 02) 873.12 – 1203.86 (Region 03) 1257.14 – 1539.66 (Region 04) 1587.63 – 1785.06 (Region 05) 2907.20 – 3134.04 (Region 06) 3341.84 – 3480.45 (Region 07)
Diesel	Diesel 191c	2827.66 – 3000.74 (Region 00) 689.92 – 899.88 (Region 01) 1129.13 – 1720.94 (Region 02) 2515.48 – 2827.41 (Region 03) 3000.98 – 3176.47 (Region 04) 3608.46 – 4477.48 (Region 05)
Ethyl benzene	Ethyl Benzene 191c	2726.89 -3185.63 (Region 00) 499.96 – 1115.89 (Region 01) 1225.08 – 1987.55 (Region 02)
Ethylene (Soy only)	Ethylene 191c	900.12 – 1000.16 (Region 00) 615.91 – 899.88 (Region 01) 1000.40 – 1141.67 (Region 02) 1341.75 – 2117.96 (Region 03) 2901.41 – 3286.87 (Region 04)
Formaldehyde	Formaldehyde 191c	2671.69 – 2785.47 (Region 00) 885.18 – 1584.50 (Region 01) 1665.74 – 1817.37 (Region 02) 2545.13 – 2671.45 (Region 03) 2785.71 – 3123.20 (Region 04) 3348.35 – 3562.66 (Region 05)
Water	H2O% 191C	1097.32 – 1168.67 (Region 00) 499.96 – 1097.08 (Region 01) 1168.67 – 4999.88 (Region 02)
Heptane	Heptane 150c	2772.69 – 2991.57 (Region 00) 708.00 – 1534.60 (Region 01) 2562.97 – 2772.45 (Region 02) 2991.81 – 3224.44 (Region 03)

		3971.97 – 4499.65 (Region 04)
Hexane	Hexane 150c	691.85 – 1507.60 (Region 00) 2543.20 – 2776.07 (Region 01) 3002.18 – 3205.16 (Region 02)
m-xylene	m-Xylene 191c	649.18 – 926.40 (Region 00) 934.36 – 1274.49 (Region 01) 1331.62 – 1987.55 (Region 02)
Nitrous oxide (N_2O)	N2O 191C	2174.14 – 2211.75 (Region 00) 519.97 – 644.12 (Region 01) 1112.99 – 1346.82 (Region 02) 1875.96 – 1887.04 (Region 03) 2124.97 – 2173.90 (Region 04) 2211.99 – 2271.29 (Region 05) 2405.32 – 2619.87 (Region 06) 2744.74 – 2828.14 (Region 07) 3291.95 – 3517.82 (Region 08)
Ammonia (NH_3)	NH3 191C	903.98 – 977.27 (Region 00) 544.32 – 903.74 (Region 01) 977.51 – 2002.99 (Region 02) 3007.98 – 3973.43 (Region 03)
Nitrogen oxide (NO)	NO 191C	1849.66 – 1939.58 (Region 00) 1705.51 – 1849.42 (Region 01) 1939.82 – 1990.44 (Region 02) 3556.13 – 3832.87 (Region 03)
Nitrogen dioxide (NO_2)	NO2 Low 191C (1of2)	1571.73 – 1633.68 (Region 00) 628.21 – 996.07 (Region 01) 1189.40 – 1421.79 (Region 02) 1522.07 – 1571.49 (Region 03) 1633.92 – 1753.49 (Region 04)
	NO2 High 191C (2of2)	2824.77 – 2948.92 (Region 00) 2763.78 – 2824.53 (Region 01)
o-xylene	o-Xylene 191c	2835.37 – 3139.35 (Region 00) 573.24 – 812.14 (Region 01) 971.96 – 1151.55 (Region 02) 1264.37 – 2028.77 (Region 03) 2706.88 – 2835.13 (Region 04) 3139.59 – 3218.66 (Region 05)
Propanal (propionaldehyde)	Propanal 191c	2606.36 – 2861.64 (Region 00) 499.96 – 713.30 (Region 01) 793.33 – 1534.36 (Region 02) 1640.91 – 1864.85 (Region 03) 2526.09 – 2606.12 (Region 04) 2861.88 – 3192.62 (Region 05) 3400.42 – 3533.72 (Region 06)
Styrene	Styrene 191c	876.26 – 1136.85 (Region 00) 662.68 – 850.22 (Region 01) 1163.12 – 1997.20 (Region 02) 2893.70 – 3206.60 (Region 03)
Toluene	Toluene 191C	2813.91 – 3149.71 (Region 00) 611.81 – 2024.92 (Region 01) 2531.39 – 2813.67 (Region 02) 3149.95 – 3283.02 (Region 03) 3949.55 – 4797.37 (Region 04)

Table A-2: Percent (%) of measurements falling below the method detection limit for all compounds analyzed using the April 2013 method

Table A-2: 1,2,4-Trimethylbenzene through Benzaldehyde											
Run #	**Bio%**	**Test Date**	**Run of Day**	**1,2,4-Trimethylbenzene**	**1,3,5-Trimethylbenzene**	**2-Heptanone**	**2-Pentanone**	**Acetaldehyde**	**Acetone**	**Acrolein**	**Benzaldehyde**
1	B000	18JUN2013	1	98%	100%	77%	84%	100%	92%	93%	99%
2	B000	25JUN2013	1	92%	100%	79%	61%	98%	98%	97%	98%
3	B000	06AUG2013	1	97%	100%	52%	68%	99%	96%	98%	98%
4	B010	29AUG2013	1	99%	100%	68%	59%	99%	88%	95%	99%
5	B010	30AUG2013	1	92%	100%	66%	59%	99%	93%	95%	99%
6	B010	31AUG2013	1	98%	100%	73%	58%	98%	85%	99%	97%
7	B020	04SEP2013	1	98%	100%	67%	74%	99%	88%	98%	99%
8	B020	05SEP2013	1	95%	100%	76%	73%	99%	91%	98%	100%
9	B020	06SEP2013	1	97%	100%	72%	80%	99%	89%	99%	100%
10	B050	09SEP2013	1	99%	100%	53%	84%	100%	88%	97%	100%
11	B050	10SEP2013	1	95%	100%	73%	80%	100%	85%	98%	99%
12	B050	11SEP2013	1	98%	100%	72%	79%	100%	89%	98%	99%
13	B100	19SEP2013	1	99%	100%	35%	93%	100%	84%	95%	100%
14	B100	20SEP2013	1	97%	100%	61%	95%	100%	89%	97%	100%
15	B100	20SEP2013	2	98%	100%	61%	95%	100%	83%	98%	100%
16	B000	22OCT2013	1	95%	100%	72%	75%	97%	84%	98%	99%
17	B000	24OCT2013	1	92%	100%	71%	79%	97%	85%	97%	99%
18	B000	25OCT2013	1	86%	100%	85%	83%	98%	89%	99%	100%
19	B000	01MAY2014	1	93%	100%	63%	74%	98%	91%	97%	99%
20	B000	02MAY2014	1	91%	100%	70%	81%	98%	88%	99%	100%
21	B010	05MAY2014	1	93%	100%	65%	81%	96%	83%	97%	100%
22	B010	06MAY2014	1	94%	100%	67%	80%	99%	85%	99%	100%
23	B010	06MAY2014	2	95%	100%	68%	81%	98%	86%	99%	100%
24	B020	07MAY2014	1	96%	100%	78%	92%	99%	93%	98%	100%
25	B020	07MAY2014	2	96%	100%	67%	85%	99%	90%	96%	99%
26	B020	12MAY2014	2	98%	100%	58%	74%	99%	89%	99%	99%
27	B020	13MAY2014	1	99%	100%	96%	96%	100%	97%	100%	100%
28	B020	13MAY2014	2	99%	100%	63%	82%	99%	91%	96%	100%
29	B020	14MAY2014	1	97%	100%	61%	78%	99%	92%	98%	99%
30	B020	15MAY2014	1	99%	100%	75%	79%	99%	87%	98%	99%
31	B050	20MAY2014	1	95%	100%	79%	89%	100%	96%	99%	100%
32	B050	20MAY2014	2	97%	100%	80%	84%	100%	95%	99%	100%
33	B050	22MAY2014	1	96%	100%	68%	84%	99%	87%	92%	100%
34	B100	23MAY2014	1	97%	100%	47%	94%	99%	84%	93%	100%
35	B100	23MAY2014	2	98%	100%	32%	92%	100%	78%	97%	100%
36	B100	26MAY2014	1	98%	100%	58%	90%	100%	78%	93%	100%
37	B000	27MAY2014	1	97%	100%	64%	69%	95%	86%	96%	99%

Table A-2 (continued): Benzene through Formaldehyde													
Run #	**Bio%**	**Test Date**	**Run of Day**	**Benzene**	**Butyraldehyde**	**CO (ppm)**	**CO (%)**	**CO_2 (%)**	**Crotonaldehyde**	**Diesel**	**Ethyl Benzene**	**Ethylene***	**Formaldehyde**
1	B000	18JUN2013	1	100%	76%	3%	4%	4%	86%	4%	90%		3%
2	B000	25JUN2013	1	99%	60%	3%	4%	4%	75%	3%	99%		3%
3	B000	06AUG2013	1	100%	19%	2%	2%	2%	63%	5%	94%		2%
4	B010	29AUG2013	1	99%	64%	2%	2%	2%	60%	2%	93%		2%
5	B010	30AUG2013	1	100%	22%	1%	1%	1%	60%	1%	98%		1%
6	B010	31AUG2013	1	100%	67%	2%	2%	2%	66%	2%	94%		2%
7	B020	04SEP2013	1	100%	57%	3%	3%	3%	60%	2%	97%		3%
8	B020	05SEP2013	1	100%	43%	2%	2%	2%	63%	1%	99%		2%
9	B020	06SEP2013	1	100%	52%	2%	2%	2%	57%	2%	94%		2%
10	B050	09SEP2013	1	100%	64%	2%	2%	2%	61%	1%	99%		2%
11	B050	10SEP2013	1	100%	70%	1%	2%	2%	70%	1%	99%		2%
12	B050	11SEP2013	1	100%	91%	2%	2%	2%	55%	1%	100%		2%
13	B100	19SEP2013	1	100%	84%	2%	2%	2%	50%	1%	100%		2%
14	B100	20SEP2013	1	100%	76%	2%	2%	3%	57%	2%	100%		2%
15	B100	20SEP2013	2	100%	77%	4%	4%	4%	52%	3%	100%		4%
16	B000	22OCT2013	1	100%	73%	2%	2%	2%	54%	1%	71%		2%
17	B000	24OCT2013	1	100%	63%	2%	2%	2%	63%	2%	63%		2%
18	B000	25OCT2013	1	100%	50%	3%	3%	3%	70%	3%	93%		3%
19	B000	01MAY2014	1	100%	32%	3%	3%	4%	72%	3%	87%	4%	3%
20	B000	02MAY2014	1	100%	43%	3%	3%	3%	76%	9%	84%	3%	4%
21	B010	05MAY2014	1	100%	64%	2%	2%	2%	71%	3%	65%	2%	2%
22	B010	06MAY2014	1	100%	37%	3%	3%	3%	68%	5%	80%	3%	3%
23	B010	06MAY2014	2	100%	34%	2%	2%	2%	72%	5%	79%	2%	2%
24	B020	07MAY2014	1	100%	41%	2%	3%	3%	80%	3%	88%	3%	3%
25	B020	07MAY2014	2	100%	15%	2%	2%	2%	74%	2%	91%	2%	2%
26	B020	12MAY2014	2	100%	18%	2%	2%	2%	60%	1%	94%	2%	2%
27	B020	13MAY2014	1	100%	85%	3%	7%	4%	95%	57%	97%	15%	17%
28	B020	13MAY2014	2	100%	19%	3%	3%	3%	72%	4%	89%	3%	3%
29	B020	14MAY2014	1	99%	30%	3%	3%	3%	74%	2%	93%	3%	3%
30	B020	15MAY2014	1	99%	47%	3%	3%	3%	72%	2%	96%	3%	3%
31	B050	20MAY2014	1	100%	56%	3%	3%	3%	71%	2%	98%	3%	4%
32	B050	20MAY2014	2	100%	13%	4%	4%	4%	58%	3%	99%	4%	4%
33	B050	22MAY2014	1	99%	87%	8%	8%	8%	64%	5%	97%	8%	8%
34	B100	23MAY2014	1	99%	86%	22%	27%	27%	46%	15%	98%	27%	23%
35	B100	23MAY2014	2	99%	81%	4%	4%	4%	37%	3%	100%	4%	4%
36	B100	26MAY2014	1	100%	89%	3%	3%	3%	16%	2%	100%	3%	3%
37	B000	27MAY2014	1	100%	76%	3%	3%	3%	56%	2%	70%	3%	3%

*Note: Ethylene was included after the WVO spectra had already been reprocessed, and thus was only quantified for the soybean oil biodiesel emissions.

Table A-2 (concluded): H_2O through Toluene																
Run #	**Bio%**	**Test Date**	**Run of Day**	**H_2O (%)**	**Heptane**	**Hexane**	***m*-Xylene**	**N_2O**	**NH_3**	**NO**	**NO_2 High**	**NO_2 Low**	***o*-Xylene**	**Propanal**	**Styrene**	**Toluene**
1	B000	18JUN2013	1	4%	74%	97%	95%	88%	18%	3%	4%	3%	100%	99%	100%	100%
2	B000	25JUN2013	1	4%	80%	93%	80%	92%	1%	3%	4%	4%	100%	96%	100%	99%
3	B000	06AUG2013	1	6%	25%	96%	57%	75%	4%	2%	6%	2%	100%	96%	100%	100%
4	B010	29AUG2013	1	2%	48%	95%	82%	82%	2%	2%	2%	2%	100%	93%	100%	100%
5	B010	30AUG2013	1	2%	24%	93%	62%	82%	2%	1%	1%	1%	100%	96%	100%	99%
6	B010	31AUG2013	1	3%	62%	94%	86%	71%	94%	2%	3%	2%	99%	94%	100%	100%
7	B020	04SEP2013	1	3%	64%	99%	81%	71%	13%	2%	3%	2%	100%	96%	100%	99%
8	B020	05SEP2013	1	2%	39%	99%	70%	71%	14%	2%	2%	2%	100%	94%	100%	99%
9	B020	06SEP2013	1	2%	41%	99%	77%	67%	83%	2%	2%	2%	100%	94%	100%	98%
10	B050	09SEP2013	1	2%	51%	99%	84%	65%	36%	2%	2%	2%	95%	84%	100%	99%
11	B050	10SEP2013	1	2%	79%	99%	89%	72%	13%	1%	2%	1%	93%	87%	100%	98%
12	B050	11SEP2013	1	2%	63%	99%	90%	70%	25%	2%	2%	2%	94%	99%	100%	100%
13	B100	19SEP2013	1	2%	46%	99%	98%	62%	71%	2%	2%	2%	51%	87%	100%	96%
14	B100	20SEP2013	1	3%	46%	98%	98%	73%	5%	2%	3%	2%	45%	86%	100%	95%
15	B100	20SEP2013	2	4%	42%	99%	92%	69%	28%	4%	4%	4%	57%	90%	100%	98%
16	B000	22OCT2013	1	2%	53%	96%	91%	73%	90%	2%	3%	2%	97%	81%	99%	99%
17	B000	24OCT2013	1	2%	52%	93%	86%	73%	88%	2%	2%	2%	100%	83%	98%	99%
18	B000	25OCT2013	1	3%	81%	94%	77%	81%	88%	3%	3%	3%	100%	88%	100%	100%
19	B000	01MAY2014	1	3%	37%	97%	86%	79%	37%	4%	5%	4%	100%	88%	87%	100%
20	B000	02MAY2014	1	3%	51%	96%	87%	87%	85%	4%	4%	3%	100%	86%	87%	100%
21	B010	05MAY2014	1	2%	66%	95%	94%	86%	88%	3%	3%	2%	98%	82%	65%	99%
22	B010	06MAY2014	1	3%	39%	96%	84%	83%	91%	4%	4%	3%	99%	82%	66%	100%
23	B010	06MAY2014	2	2%	47%	95%	77%	77%	93%	3%	3%	2%	99%	86%	71%	99%
24	B020	07MAY2014	1	3%	28%	98%	85%	85%	94%	4%	3%	3%	99%	90%	78%	100%
25	B020	07MAY2014	2	2%	26%	98%	81%	77%	90%	2%	2%	2%	99%	94%	76%	100%
26	B020	12MAY2014	2	2%	18%	99%	68%	78%	91%	2%	2%	2%	100%	95%	75%	100%
27	B020	13MAY2014	1	3%	75%	99%	98%	100%	99%	4%	22%	3%	100%	96%	93%	100%
28	B020	13MAY2014	2	3%	28%	98%	82%	82%	94%	4%	3%	3%	100%	92%	78%	100%
29	B020	14MAY2014	1	0%	20%	99%	82%	79%	87%	3%	3%	3%	100%	90%	78%	100%
30	B020	15MAY2014	1	0%	38%	99%	89%	84%	89%	3%	3%	3%	100%	96%	77%	100%
31	B050	20MAY2014	1	3%	32%	99%	86%	73%	99%	3%	3%	3%	93%	96%	97%	99%
32	B050	20MAY2014	2	4%	12%	99%	68%	81%	88%	4%	4%	4%	97%	97%	97%	100%
33	B050	22MAY2014	1	8%	75%	99%	99%	83%	92%	8%	8%	8%	89%	90%	87%	98%
34	B100	23MAY2014	1	9%	57%	99%	98%	82%	39%	28%	26%	27%	55%	80%	79%	97%
35	B100	23MAY2014	2	4%	63%	100%	98%	79%	81%	4%	4%	4%	47%	80%	27%	96%
36	B100	26MAY2014	1	3%	39%	100%	100%	79%	3%	3%	3%	3%	13%	77%	28%	97%
37	B000	27MAY2014	1	2%	29%	97%	92%	72%	80%	3%	3%	3%	95%	80%	70%	100%

B. Appendix B – Two-Way ANOVA Summary Tables

Table B-1: ANOVA summary statistics for formaldehyde emission rates

Effect on Formaldehyde Emission Rate (µg/s)															
Waste Vegetable Oil (WVO) Biodiesel					Soybean Oil (SOY) Biodiesel										
Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F						
Bio%	4	740219162.9	6811.731	<.0001	Bio%	4	491123903.9	7278.1481	<.0001						
Phase	2	13691040558	251978.5772	<.0001	Phase	2	12035622483	356720.745	<.0001						
Bio%*Phase	8	1219207077	5609.7647	<.0001	Bio%*Phase	8	710420322.2	5263.9917	<.0001						
Phase 5					Phase 7					Phase 9					
Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F	
Feedstock	1	6863597.703	106.0648	<.0001	Feedstock	1	2199743	1207.9363	<.0001	Feedstock	1	1950581.5	5071.3775	<.0001	
Bio%	4	2030350593	7843.8738	<.0001	Bio%	4	29404814	4036.7383	<.0001	Bio%	4	3666435.4	2383.1199	<.0001	
Feedstock*Bio%	4	509511109.8	1968.3994	<.0001	Feedstock*Bio%	4	9981184	1370.2324	<.0001	Feedstock*Bio%	4	1082123.8	703.3618	<.0001	
B0					B10					B20					
Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F	
Feedstock	1	79330388.16	1606.0225	<.0001	Feedstock	1	27594881.44	1410.8395	<.0001	Feedstock	1	25804035.89	3615.9687	<.0001	
Phase	2	8283875282	83852.4184	<.0001	Phase	2	7460967010	190727.89	<.0001	Phase	2	5293313290	370881.0354	<.0001	
Feedstock*Phase	2	80310974.04	812.9371	<.0001	Feedstock*Phase	2	65843730.62	1683.1914	<.0001	Feedstock*Phase	2	16899087.23	1184.0506	<.0001	
					B50					B100					
					Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F	
					Feedstock	1	46477875.14	1675.1123	<.0001	Feedstock	1	66329548.67	16722.1043	<.0001	
					Phase	2	2886358932	52013.732	<.0001	Phase	2	2989202353	376798.5355	<.0001	
					Feedstock*Phase	2	44676992.42	805.1033	<.0001	Feedstock*Phase	2	83218278.94	10489.9307	<.0001	

Table B-2: ANOVA summary statistics for carbon dioxide (CO_2) emission rates

Effect on Carbon Dioxide (CO_2) Emission Rate (mg/s)															
Waste Vegetable Oil (WVO) Biodiesel					Soybean Oil (SOY) Biodiesel										
Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F						
Bio%	4	83428393.261	506.3816	<.0001	Bio%	4	790453468.7	6816.7325	<.0001						
Phase	2	58845110796	714339.0716	<.0001	Phase	2	30557231057	527040.435	<.0001						
Bio%*Phase	8	74513050.01	226.1343	<.0001	Bio%*Phase	8	240935485.5	1038.8927	<.0001						
Phase 5					Phase 7					Phase 9					
Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F	
Feedstock	1	443206042	78271.1378	<.0001	Feedstock	1	871229335	40203.2401	<.0001	Feedstock	1	5494725843	69573.905	<.0001	
Bio%	4	11696175	516.3924	<.0001	Bio%	4	174469975	2012.7474	<.0001	Bio%	4	535734913.8	1695.8612	<.0001	
Feedstock*Bio%	4	47166180	2082.4121	<.0001	Feedstock*Bio%	4	63429142	731.741	<.0001	Feedstock*Bio%	4	370435558.2	1172.6085	<.0001	
B0					B10					B20					
Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F	
Feedstock	1	1335682431	33415.0206	<.0001	Feedstock	1	1247980938	41183.7526	<.0001	Feedstock	1	1558549394	58770.0466	<.0001	
Phase	2	14470670792	181007.7572	<.0001	Phase	2	16336341068	269552.126	<.0001	Phase	2	21116302018	398128.5605	<.0001	
Feedstock*Phase	2	393846346.2	4926.4644	<.0001	Feedstock*Phase	2	357374788.8	5896.7387	<.0001	Feedstock*Phase	2	473513447.6	8927.663	<.0001	
					B50					B100					
					Factor	DF	Sum of Squares	F ratio	Prob > F	Factor	DF	Sum of Squares	F ratio	Prob > F	
					Feedstock	1	1295532795	41923.2471	<.0001	Feedstock	1	207130137.6	4121.0095	<.0001	
					Phase	2	15946047873	258005.86	<.0001	Phase	2	19423997786	193227.5041	<.0001	
					Feedstock*Phase	2	446894506	7230.7196	<.0001	Feedstock*Phase	2	82428351.18	819.9869	<.0001	

Table B-3: ANOVA summary statistics for carbon monoxide (CO) emission rates

Effect on Carbon Monoxide (CO) Emission Rate (µg/s)

Waste Vegetable Oil (WVO) Biodiesel

Factor	DF	Sum of Squares	F ratio	Prob > F
Bio%	4	1.9819E+11	11759.0508	<.0001
Phase	2	2.42E+12	287629.3003	<.0001
Bio%*Phase	8	57921718500	1718.3094	<.0001

Soybean Oil (SOY) Biodiesel

Factor	DF	Sum of Squares	F ratio	Prob > F
Bio%	4	1.00218E+11	8274.924	<.0001
Phase	2	1.88E+12	311001.149	<.0001
Bio%*Phase	8	28240422844	1165.8982	<.0001

Phase 5

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	28314070484	3286.1513	<.0001
Bio%	4	1.62294E+11	4708.9787	<.0001
Feedstock*Bio%	4	79626856657	2310.3875	<.0001

Phase 7

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	3243600799	1810.1053	<.0001
Bio%	4	37784507956	5271.4517	<.0001
Feedstock*Bio%	4	9328403872	1301.439	<.0001

Phase 9

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	6749580663	12327.7858	<.0001
Bio%	4	17641210731	8055.2066	<.0001
Feedstock*Bio%	4	3827492705	1747.683	<.0001

B0

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	44439977643	6793.2131	<.0001
Phase	2	1.047093E+12	80030.7335	<.0001
Feedstock*Phase	2	13293552491	1016.0439	<.0001

B10

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	3200493.854	1.1535	0.2828
Phase	2	9.83882E+11	177300.999	<.0001
Feedstock*Phase	2	782644416.8	141.0369	<.0001

B20

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	18070114884	11182.1689	<.0001
Phase	2	9.77841E+11	302554.3536	<.0001
Feedstock*Phase	2	6005636162	1858.2073	<.0001

B50

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	24637946890	4595.0048	<.0001
Phase	2	6.34498E+11	59167.3135	<.0001
Feedstock*Phase	2	8519424889	794.4412	<.0001

B100

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	9771627710	5699.5762	<.0001
Phase	2	6.91385E+11	201634.8276	<.0001
Feedstock*Phase	2	8012815045	2336.8496	<.0001

Note that for B10 blends, feedstock did not test as having had a statistically significant effect on CO emissions.

Table B-4: ANOVA summary statistics for nitric oxide (NO) emission rates

Effect on NO Emission Rate (µg/s)

Waste Vegetable Oil (WVO) Biodiesel

Factor	DF	Sum of Squares	F ratio	Prob > F
Bio%	4	2.3311E+10	1623.9403	<.0001
Phase	2	5.4617E+12	760977.6634	<.0001
Bio%*Phase	8	1.3718E+10	477.8407	<.0001

Soybean Oil (SOY) Biodiesel

Factor	DF	Sum of Squares	F ratio	Prob > F
Bio%	4	17057031722	2218.6765	<.0001
Phase	2	3.11E+12	808834.1285	<.0001
Bio%*Phase	8	18475386477	1201.5838	<.0001

Phase 5

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	877017177.3	15906.6941	<.0001
Bio%	4	1564895518	7095.7317	<.0001
Feedstock*Bio%	4	311774046.9	1413.6822	<.0001

Phase 7

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	12730790882	15302.5777	<.0001
Bio%	4	3298701769	991.2707	<.0001
Feedstock*Bio%	4	2983232407	896.4711	<.0001

Phase 9

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	2.21232E+11	29418.8895	<.0001
Bio%	4	50461646842	1677.5685	<.0001
Feedstock*Bio%	4	21014074967	698.6009	<.0001

B0

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	46387635247	13032.3446	<.0001
Phase	2	1.442722E+12	202662.3573	<.0001
Feedstock*Phase	2	39738805195	5582.1966	<.0001

B10

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	6003047818	3853.0296	<.0001
Phase	2	1.47E+12	473135.5751	<.0001
Feedstock*Phase	2	6571944126	2109.0866	<.0001

B20

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	52606011960	22518.1987	<.0001
Phase	2	2.07E+12	442518.2465	<.0001
Feedstock*Phase	2	43231673349	9252.7391	<.0001

B50

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	19629608241	6201.1064	<.0001
Phase	2	1.53E+12	240956.5937	<.0001
Feedstock*Phase	2	22734248505	3590.9401	<.0001

B100

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	18823629299	5818.3077	<.0001
Phase	2	1.93E+12	298896.6843	<.0001
Feedstock*Phase	2	12187902449	1883.6157	<.0001

Table B-5: ANOVA summary statistics for nitrogen dioxide (NO_2) emission rates

Effect on NO_2 Emission Rate (µg/s)

Waste Vegetable Oil (WVO) Biodiesel

Factor	DF	Sum of Squares	F ratio	Prob > F
Bio%	4	3337259250	5728.0919	<.0001
Phase	2	8037664458	27591.7915	<.0001
Bio%*Phase	8	1351586151	1159.9353	<.0001

Soybean Oil (SOY) Biodiesel

Factor	DF	Sum of Squares	F ratio	Prob > F
Bio%	4	1463840604	3806.5277	<.0001
Phase	2	3546914116	18446.5807	<.0001
Bio%*Phase	8	1032817203	1342.8536	<.0001

Phase 5

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	2541626016	24900.7599	<.0001
Bio%	4	529873247.8	1297.8155	<.0001
Feedstock*Bio%	4	709863640.8	1738.6649	<.0001

Phase 7

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	1073847563	6426.0191	<.0001
Bio%	4	1147407507	1716.5524	<.0001
Feedstock*Bio%	4	1048453945	1568.5152	<.0001

Phase 9

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	280318202.8	2905.8555	<.0001
Bio%	4	1588725397	4117.291	<.0001
Feedstock*Bio%	4	979051305.8	2537.2787	<.0001

B0

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	3202941293	18690.3745	<.0001
Phase	2	1758459162	5130.6373	<.0001
Feedstock*Phase	2	8488380.01	24.7665	<.0001

B10

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	108887763	1243.1736	<.0001
Phase	2	1408750835	8041.8675	<.0001
Feedstock*Phase	2	257232152	1468.4122	<.0001

B20

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	2128971345	19772.1094	<.0001
Phase	2	2496116943	11590.9257	<.0001
Feedstock*Phase	2	255285420.1	1185.439	<.0001

B50

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	559562720.9	3754.3587	<.0001
Phase	2	2940674112	9865.1546	<.0001
Feedstock*Phase	2	215985240.4	724.5712	<.0001

B100

Factor	DF	Sum of Squares	F ratio	Prob > F
Feedstock	1	34365447.08	410.3537	<.0001
Phase	2	4081938208	24370.9713	<.0001
Feedstock*Phase	2	71866586.17	429.0752	<.0001

C. Appendix C – Student's t-Test Summary Tables

Table C-1: Formaldehyde pairwise Student's t-test summary statistics – Effect of BLEND for WVO runs

		Table C-1: Formaldehyde ER Pairwise Student's t-test Summary Effect of Blend (Bio%) for WVO Runs, by Phase							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange** = 0.0001 < p < 0.05		
		Bio%	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
WVO B0 vs. Bxx	Phase 5	10	456.26	4.269322	63176	106.87	<.0001	447.89	464.63
		20	676.03	4.269322	63176	158.35	<.0001	667.66	684.4
		50	848.83	4.261574	63176	199.18	<.0001	840.47	857.18
		100	1139.04	4.265439	63176	267.04	<.0001	1130.68	1147.4
	Phase 7	10	18.96	4.264236	63176	4.45	<.0001	10.6	27.32
		20	56.87	4.260327	63176	13.35	<.0001	48.52	65.22
		50	43.25	4.260327	63176	10.15	<.0001	34.9	51.6
		100	2.53	4.252563	63176	0.6	0.5515	-5.8	10.87
	Phase 9	10	19.16	4.260242	63176	4.5	<.0001	10.81	27.51
		20	32.92	4.271957	63176	7.71	<.0001	24.55	41.3
		50	45.93	4.260242	63176	10.78	<.0001	37.58	54.28
		100	42.91	4.268034	63176	10.05	<.0001	34.55	51.28
WVO B10 vs. Bxx	Phase 5	20	219.77	4.931805	63176	44.56	<.0001	210.1	229.44
		50	392.57	4.9251	63176	79.71	<.0001	382.91	402.22
		100	682.78	4.928444	63176	138.54	<.0001	673.12	692.44
	Phase 7	20	37.91	4.935182	63176	7.68	<.0001	28.23	47.58
		50	24.29	4.935182	63176	4.92	<.0001	14.62	33.97
		100	-16.43	4.928481	63176	-3.33	0.0009	-26.09	-6.77
	Phase 9	20	13.77	4.935219	63176	2.79	0.0053	4.09	23.44
		50	26.77	4.925081	63176	5.44	<.0001	17.11	36.42
		100	23.76	4.931823	63176	4.82	<.0001	14.09	33.42
WVO B20 vs. Bxx	Phase 5	50	172.8	4.9251	63176	35.08	<.0001	163.14	182.45
		100	463.01	4.928444	63176	93.95	<.0001	453.35	472.67
	Phase 7	50	-13.61	4.931805	63176	-2.76	0.0058	-23.28	-3.95
		100	-54.33	4.9251	63176	-11.03	<.0001	-63.99	-44.68
	Phase 9	50	13	4.935219	63176	2.63	0.0084	3.33	22.67
		100	9.99	4.941947	63176	2.02	0.0433	0.3	19.68
WVO B50 vs. B100	Phase 5	100	290.21	4.921734	63176	58.97	<.0001	280.57	299.86
	Phase 7	100	-40.72	4.9251	63176	-8.27	<.0001	-50.37	-31.07
	Phase 9	100	-3.01	4.931823	63176	-0.61	0.5413	-12.68	6.65

Table C-2: Formaldehyde pairwise Student's t-test summary statistics – Effect of BLEND for SOY runs

		Table C-2: Formaldehyde ER Pairwise Student's t-test Summary Effect of Blend (Bio%) for SOY Runs, by Phase							
		Compared factor	green = REDUCTION in emissions				red = SIGNIFICANT difference (<0.0001) orange = 0.0001 < p < 0.05		
		Bio%	Difference	Std Error	DF	t Ratio	Prob > |t|	Lower 95%	Upper 95%
SOY B0 vs. Bxx	Phase 5	10	-270.35	5.494303	63176	-49.21	<.0001	-281.12	-259.58
		20	451.79	5.015829	63176	90.07	<.0001	441.96	461.62
		50	747.05	5.477326	63176	136.39	<.0001	736.31	757.79
		100	335.12	5.468161	63176	61.29	<.0001	324.4	345.83
	Phase 7	10	-50.84	5.476241	63176	-9.28	<.0001	-61.57	-40.11
		20	35.63	5.016882	63176	7.1	<.0001	25.8	45.46
		50	38.21	5.465805	63176	6.99	<.0001	27.5	48.92
		100	-117.17	5.36957	63176	-21.82	<.0001	-127.7	-106.65
	Phase 9	10	9.17	5.450718	63176	1.68	0.0926	-1.51	19.85
		20	30.67	4.998302	63176	6.14	<.0001	20.87	40.47
		50	34.02	5.461352	63176	6.23	<.0001	23.31	44.72
		100	0.95	5.42717	63176	0.17	0.8616	-9.69	11.58
SOY B10 vs. Bxx	Phase 5	20	722.14	4.366922	63176	165.37	<.0001	713.58	730.7
		50	1017.4	4.890048	63176	208.05	<.0001	1007.81	1026.98
		100	605.47	4.879779	63176	124.08	<.0001	595.9	615.03
	Phase 7	20	86.47	4.365654	63176	19.81	<.0001	77.91	95.03
		50	89.05	4.874921	63176	18.27	<.0001	79.49	98.6
		100	-66.33	4.766772	63176	-13.92	<.0001	-75.68	-56.99
	Phase 9	20	21.5	4.371885	63176	4.92	<.0001	12.93	30.07
		50	24.85	4.89456	63176	5.08	<.0001	15.25	34.44
		100	-8.22	4.85639	63176	-1.69	0.0904	-17.74	1.3
SOY B20 vs. Bxx	Phase 5	50	295.26	4.345543	63176	67.95	<.0001	286.74	303.78
		100	-116.67	4.333984	63176	-26.92	<.0001	-125.17	-108.18
	Phase 7	50	2.58	4.352555	63176	0.59	0.5535	-5.95	11.11
		100	-152.8	4.231076	63176	-36.11	<.0001	-161.1	-144.51
	Phase 9	50	3.35	4.385137	63176	0.76	0.4454	-5.25	11.94
		100	-29.72	4.342491	63176	-6.84	<.0001	-38.23	-21.21
SOY B50 vs. B100	Phase 5	100	-411.93	4.860656	63176	-84.75	<.0001	-421.46	-402.41
	Phase 7	100	-155.38	4.754779	63176	-32.68	<.0001	-164.7	-146.06
	Phase 9	100	-33.07	4.868323	63176	-6.79	<.0001	-42.61	-23.53

Table C-3: Formaldehyde pairwise Student's t-test summary statistics – Effect of PHASE and FEEDSTOCK

		Table C-3: Formaldehyde ER Pairwise Student's t-test Summary Effect of Phase by Feedstock and Fuel Blend							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange** = 0.0001 < p < 0.05		
		Phase	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
WVO	B0	5 vs. 7	1913.77	3.472002	63176	551.2	<.0001	1906.97	1920.58
		5 vs. 9	2102.26	3.476666	63176	604.68	<.0001	2095.45	2109.08
		7 vs. 9	188.49	3.465615	63176	54.39	<.0001	181.7	195.28
	B10	5 vs. 7	1476.47	4.935182	63176	299.17	<.0001	1466.8	1486.14
		5 vs. 9	1665.16	4.928444	63176	337.87	<.0001	1655.5	1674.82
		7 vs. 9	188.69	4.931823	63176	38.26	<.0001	179.02	198.35
	B20	5 vs. 7	1294.61	4.931805	63176	262.5	<.0001	1284.94	1304.27
		5 vs. 9	1459.15	4.938575	63176	295.46	<.0001	1449.47	1468.83
		7 vs. 9	164.54	4.938575	63176	33.32	<.0001	154.87	174.22
	B50	5 vs. 7	1108.2	4.9251	63176	225.01	<.0001	1098.54	1117.85
		5 vs. 9	1299.36	4.921734	63176	264	<.0001	1289.71	1309.01
		7 vs. 9	191.16	4.928444	63176	38.79	<.0001	181.5	200.82
	B100	5 vs. 7	777.26	4.921734	63176	157.92	<.0001	767.62	786.91
		5 vs. 9	1006.13	4.931823	63176	204.01	<.0001	996.47	1015.8
		7 vs. 9	228.87	4.928481	63176	46.44	<.0001	219.21	238.53
SOY	B0	5 vs. 7	1569.14	6.015617	63176	260.84	<.0001	1557.35	1580.93
		5 vs. 9	1726.54	5.993992	63176	288.05	<.0001	1714.79	1738.29
		7 vs. 9	157.4	5.986625	63176	26.29	<.0001	145.67	169.13
	B10	5 vs. 7	1788.65	4.89785	63176	365.19	<.0001	1779.05	1798.25
		5 vs. 9	2006.06	4.895891	63176	409.74	<.0001	1996.46	2015.66
		7 vs. 9	217.41	4.884656	63176	44.51	<.0001	207.84	226.98
	B20	5 vs. 7	1152.98	3.760319	63176	306.62	<.0001	1145.61	1160.35
		5 vs. 9	1305.42	3.770097	63176	346.26	<.0001	1298.03	1312.81
		7 vs. 9	152.44	3.78318	63176	40.29	<.0001	145.03	159.86
	B50	5 vs. 7	860.3	4.867081	63176	176.76	<.0001	850.76	869.84
		5 vs. 9	1013.51	4.888715	63176	207.32	<.0001	1003.93	1023.09
		7 vs. 9	153.21	4.884845	63176	31.36	<.0001	143.63	162.78
	B100	5 vs. 7	1116.85	4.748202	63176	235.22	<.0001	1107.54	1126.16
		5 vs. 9	1392.37	4.840146	63176	287.67	<.0001	1382.88	1401.86
		7 vs. 9	275.52	4.737803	63176	58.15	<.0001	266.24	284.81
		Compared factor	**Effect of Feedstock by Fuel Blend and Phase**						
		Feedstock	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
B0	Phase 5	WVO vs. SOY	409.05	4.919727	63176	83.14	<.0001	399.41	418.69
	Phase 7	WVO vs. SOY	64.42	4.902931	63176	13.14	<.0001	54.81	74.03
	Phase 9	WVO vs. SOY	33.33	4.879696	63176	6.83	<.0001	23.77	42.89
B10	Phase 5	WVO vs. SOY	-317.56	4.920444	63176	-64.54	<.0001	-327.21	-307.92
	Phase 7	WVO vs. SOY	-5.38	4.912656	63176	-1.1	0.2733	-15.01	4.25
	Phase 9	WVO vs. SOY	23.34	4.903932	63176	4.76	<.0001	13.73	32.95
B20	Phase 5	WVO vs. SOY	184.81	4.379719	63176	42.2	<.0001	176.22	193.39
	Phase 7	WVO vs. SOY	43.18	4.390986	63176	9.83	<.0001	34.57	51.79
	Phase 9	WVO vs. SOY	31.08	4.40695	63176	7.05	<.0001	22.44	39.71
B50	Phase 5	WVO vs. SOY	307.27	4.894733	63176	62.78	<.0001	297.68	316.86
	Phase 7	WVO vs. SOY	59.37	4.89762	63176	12.12	<.0001	49.77	68.97
	Phase 9	WVO vs. SOY	21.42	4.91575	63176	4.36	<.0001	11.78	31.05
B100	Phase 5	WVO vs. SOY	-394.87	4.887846	63176	-80.79	<.0001	-404.45	-385.29
	Phase 7	WVO vs. SOY	-55.29	4.783079	63176	-11.56	<.0001	-64.66	-45.91
	Phase 9	WVO vs. SOY	-8.64	4.884553	63176	-1.77	0.077	-18.21	0.94

Table C-4: CO_2 pairwise Student's t-test summary statistics – Effect of BLEND for WVO runs

		Table C-4: CO_2 ER Pairwise Student's t-test Full Summary Effect of Blend (Bio%) for WVO Runs, by Phase							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange =** 0.0001 < p < 0.05		
		Bio%	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
WVO B0 vs. Bxx	Phase 5	10	-34.25	5.382167	63176	-6.36	<.0001	-44.8	-23.7
		20	-33.48	5.382167	63176	-6.22	<.0001	-44.03	-22.93
		50	21.49	5.3724	63176	4	<.0001	10.96	32.02
		100	62.48	5.377273	63176	11.62	<.0001	51.94	73.02
	Phase 7	10	-39.87	5.375756	63176	-7.42	<.0001	-50.4	-29.33
		20	-106.48	5.370829	63176	-19.82	<.0001	-117	-95.95
		50	-134.51	5.370829	63176	-25.04	<.0001	-145.03	-123.98
		100	-137	5.361041	63176	-25.55	<.0001	-147.51	-126.49
	Phase 9	10	-180.03	5.370721	63176	-33.52	<.0001	-190.56	-169.51
		20	-263.36	5.38549	63176	-48.9	<.0001	-273.91	-252.8
		50	-188.48	5.370721	63176	-35.09	<.0001	-199.01	-177.95
		100	-164.38	5.380544	63176	-30.55	<.0001	-174.92	-153.83
WVO B10 vs. Bxx	Phase 5	20	0.77	6.217334	63176	0.12	0.9018	-11.42	12.95
		50	55.73	6.208881	63176	8.98	<.0001	43.57	67.9
		100	96.73	6.213097	63176	15.57	<.0001	84.55	108.91
	Phase 7	20	-66.61	6.221591	63176	-10.71	<.0001	-78.8	-54.41
		50	-94.64	6.221591	63176	-15.21	<.0001	-106.83	-82.44
		100	-97.13	6.213144	63176	-15.63	<.0001	-109.31	-84.96
	Phase 9	20	-83.32	6.221638	63176	-13.39	<.0001	-95.52	-71.13
		50	-8.45	6.208858	63176	-1.36	0.1738	-20.61	3.72
		100	15.66	6.217357	63176	2.52	**0.0118**	3.47	27.84
WVO B20 vs. Bxx	Phase 5	50	54.97	6.208881	63176	8.85	<.0001	42.8	67.14
		100	95.96	6.213097	63176	15.45	<.0001	83.78	108.14
	Phase 7	50	-28.03	6.217334	63176	-4.51	<.0001	-40.22	-15.84
		100	-30.53	6.208881	63176	-4.92	<.0001	-42.69	-18.36
	Phase 9	50	74.88	6.221638	63176	12.04	<.0001	62.68	87.07
		100	98.98	6.23012	63176	15.89	<.0001	86.77	111.19
WVO B50 vs. B100	Phase 5	100	40.99	6.204638	63176	6.61	<.0001	28.83	53.16
	Phase 7	100	-2.5	6.208881	63176	-0.4	0.6877	-14.67	9.67
	Phase 9	100	24.1	6.217357	63176	3.88	**0.0001**	11.92	36.29

Table C-5: CO_2 pairwise Student's t-test summary statistics – Effect of BLEND for SOY runs

		Table C-5: CO_2 ER Pairwise Student's t-test Full Summary Effect of Blend (Bio%) for SOY runs, by Phase							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange** = 0.0001 < p < 0.05		
		Bio%	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
SOY B0 vs. Bxx	Phase 5	10	-31.25	6.926454	63176	-4.51	<.0001	-44.82	-17.67
		20	-53.82	6.32326	63176	-8.51	<.0001	-66.21	-41.43
		50	-37.55	6.905052	63176	-5.44	<.0001	-51.09	-24.02
		100	-200.98	6.893497	63176	-29.15	<.0001	-214.49	-187.47
	Phase 7	10	-64.21	6.903683	63176	-9.3	<.0001	-77.74	-50.68
		20	-122.37	6.324587	63176	-19.35	<.0001	-134.77	-109.97
		50	-126.84	6.890527	63176	-18.41	<.0001	-140.34	-113.33
		100	-429.42	6.769208	63176	-63.44	<.0001	-442.69	-416.15
	Phase 9	10	-223.39	6.871507	63176	-32.51	<.0001	-236.86	-209.92
		20	-293.28	6.301165	63176	-46.54	<.0001	-305.63	-280.93
		50	-167.81	6.884913	63176	-24.37	<.0001	-181.3	-154.31
		100	-877.26	6.841821	63176	-128.22	<.0001	-890.67	-863.85
SOY B10 vs. Bxx	Phase 5	20	-22.57	5.505208	63176	-4.1	<.0001	-33.36	-11.78
		50	-6.3	6.164692	63176	-1.02	0.3066	-18.39	5.78
		100	-169.73	6.151747	63176	-27.59	<.0001	-181.79	-157.67
	Phase 7	20	-58.16	5.503609	63176	-10.57	<.0001	-68.95	-47.37
		50	-62.63	6.145622	63176	-10.19	<.0001	-74.67	-50.58
		100	-365.21	6.009283	63176	-60.77	<.0001	-376.98	-353.43
	Phase 9	20	-69.89	5.511465	63176	-12.68	<.0001	-80.7	-59.09
		50	55.58	6.170381	63176	9.01	<.0001	43.49	67.68
		100	-653.87	6.122262	63176	-106.8	<.0001	-665.87	-641.87
SOY B20 vs. Bxx	Phase 5	50	16.27	5.478256	63176	2.97	**0.003**	5.53	27.01
		100	-147.16	5.463685	63176	-26.93	<.0001	-157.87	-136.45
	Phase 7	50	-4.47	5.487097	63176	-0.81	0.4153	-15.22	6.29
		100	-307.05	5.333952	63176	-57.56	<.0001	-317.5	-296.59
	Phase 9	50	125.48	5.528171	63176	22.7	<.0001	114.64	136.31
		100	-583.98	5.474409	63176	-106.67	<.0001	-594.71	-573.25
SOY B50 vs. B100	Phase 5	100	-163.43	6.12764	63176	-26.67	<.0001	-175.44	-151.42
	Phase 7	100	-302.58	5.994164	63176	-50.48	<.0001	-314.33	-290.83
	Phase 9	100	-709.46	6.137305	63176	-115.6	<.0001	-721.48	-697.43

Table C-6: CO_2 pairwise Student's t-test summary statistics – Effect of PHASE and FEEDSTOCK

		Table C-6: CO_2 ER Pairwise Student's t-test Full Summary Effect of Phase by Feedstock and Fuel Blend							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange** = 0.0001 < p < 0.05		
		Phase	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
WVO	B0	5 vs. 7	-582.53	4.377018	63176	-133.09	<.0001	-591.11	-573.96
		5 vs. 9	-3059.54	4.382897	63176	-698.06	<.0001	-3068.13	-3050.95
		7 vs. 9	-2477	4.368966	63176	-566.95	<.0001	-2485.57	-2468.44
	B10	5 vs. 7	-588.15	6.221591	63176	-94.53	<.0001	-600.35	-575.96
		5 vs. 9	-3205.32	6.213097	63176	-515.9	<.0001	-3217.5	-3193.15
		7 vs. 9	-2617.17	6.217357	63176	-420.95	<.0001	-2629.36	-2604.98
	B20	5 vs. 7	-655.53	6.217334	63176	-105.44	<.0001	-667.72	-643.34
		5 vs. 9	-3289.42	6.225868	63176	-528.35	<.0001	-3301.62	-3277.21
		7 vs. 9	-2633.89	6.225868	63176	-423.06	<.0001	-2646.09	-2621.68
	B50	5 vs. 7	-738.53	6.208881	63176	-118.95	<.0001	-750.7	-726.36
		5 vs. 9	-3269.5	6.204638	63176	-526.95	<.0001	-3281.67	-3257.34
		7 vs. 9	-2530.98	6.213097	63176	-407.36	<.0001	-2543.16	-2518.8
	B100	5 vs. 7	-782.02	6.204638	63176	-126.04	<.0001	-794.18	-769.86
		5 vs. 9	-3286.4	6.217357	63176	-528.58	<.0001	-3298.58	-3274.21
		7 vs. 9	-2504.38	6.213144	63176	-403.08	<.0001	-2516.56	-2492.2
SOY	B0	5 vs. 7	-465.66	7.583654	63176	-61.4	<.0001	-480.53	-450.8
		5 vs. 9	-2210.55	7.556392	63176	-292.54	<.0001	-2225.36	-2195.74
		7 vs. 9	-1744.89	7.547104	63176	-231.2	<.0001	-1759.68	-1730.09
	B10	5 vs. 7	-498.63	6.174529	63176	-80.76	<.0001	-510.73	-486.52
		5 vs. 9	-2402.69	6.172059	63176	-389.28	<.0001	-2414.79	-2390.59
		7 vs. 9	-1904.06	6.157895	63176	-309.21	<.0001	-1916.13	-1891.99
	B20	5 vs. 7	-534.21	4.740487	63176	-112.69	<.0001	-543.5	-524.92
		5 vs. 9	-2450.01	4.752814	63176	-515.49	<.0001	-2459.33	-2440.7
		7 vs. 9	-1915.8	4.769307	63176	-401.69	<.0001	-1925.15	-1906.45
	B50	5 vs. 7	-554.95	6.135739	63176	-90.45	<.0001	-566.98	-542.92
		5 vs. 9	-2340.8	6.163012	63176	-379.81	<.0001	-2352.88	-2328.72
		7 vs. 9	-1785.85	6.158134	63176	-290	<.0001	-1797.92	-1773.78
	B100	5 vs. 7	-694.1	5.985873	63176	-115.96	<.0001	-705.83	-682.37
		5 vs. 9	-2886.83	6.101784	63176	-473.11	<.0001	-2898.79	-2874.87
		7 vs. 9	-2192.73	5.972764	63176	-367.12	<.0001	-2204.44	-2181.02
		Compared factor	**Effect of Feedstock by Fuel Blend and Phase**						
		Feedstock	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
B0	Phase 5	WVO vs. SOY	371.22	6.202108	63176	59.85	<.0001	359.06	383.38
	Phase 7	WVO vs. SOY	488.09	6.180934	63176	78.97	<.0001	475.98	500.21
	Phase 9	WVO vs. SOY	1220.21	6.151642	63176	198.36	<.0001	1208.15	1232.27
B10	Phase 5	WVO vs. SOY	374.22	6.203011	63176	60.33	<.0001	362.06	386.38
	Phase 7	WVO vs. SOY	463.75	6.193194	63176	74.88	<.0001	451.61	475.89
	Phase 9	WVO vs. SOY	1176.86	6.182196	63176	190.36	<.0001	1164.74	1188.97
B20	Phase 5	WVO vs. SOY	350.88	5.521341	63176	63.55	<.0001	340.06	361.7
	Phase 7	WVO vs. SOY	472.2	5.535545	63176	85.3	<.0001	461.35	483.05
	Phase 9	WVO vs. SOY	1190.29	5.55567	63176	214.25	<.0001	1179.4	1201.18
B50	Phase 5	WVO vs. SOY	312.18	6.170598	63176	50.59	<.0001	300.09	324.28
	Phase 7	WVO vs. SOY	495.76	6.174238	63176	80.29	<.0001	483.66	507.86
	Phase 9	WVO vs. SOY	1240.88	6.197094	63176	200.24	<.0001	1228.74	1253.03
B100	Phase 5	WVO vs. SOY	107.76	6.161917	63176	17.49	<.0001	95.68	119.84
	Phase 7	WVO vs. SOY	195.68	6.029841	63176	32.45	<.0001	183.86	207.49
	Phase 9	WVO vs. SOY	507.32	6.157765	63176	82.39	<.0001	495.25	519.39

Table C-7: CO pairwise Student's t-test summary statistics – Effect of BLEND on WVO runs

		Table C-7: CO ER Pairwise Student's t-test Full Summary Effect of Blend (Bio%) for WVO runs, by Phase							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange** = 0.0001 < p < 0.05		
		Bio%	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
WVO B0 vs. Bxx	Phase 5	10	4564	54.65954	63176	83.5	<.0001	4456.9	4671.2
		20	6239.2	54.65954	63176	114.15	<.0001	6132.1	6346.3
		50	8288.7	54.56035	63176	151.92	<.0001	8181.8	8395.7
		100	11920.3	54.60983	63176	218.28	<.0001	11813.2	12027.3
	Phase 7	10	1732.1	54.59442	63176	31.73	<.0001	1625.1	1839.1
		20	3038.7	54.54438	63176	55.71	<.0001	2931.8	3145.6
		50	3770.6	54.54438	63176	69.13	<.0001	3663.7	3877.6
		100	4481.3	54.44498	63176	82.31	<.0001	4374.6	4588
	Phase 9	10	1078.5	54.54329	63176	19.77	<.0001	971.6	1185.4
		20	2191.2	54.69328	63176	40.06	<.0001	2084	2298.4
		50	2913.6	54.54329	63176	53.42	<.0001	2806.7	3020.5
		100	3403.4	54.64305	63176	62.28	<.0001	3296.3	3510.5
WVO B10 vs. Bxx	Phase 5	20	1675.2	63.14122	63176	26.53	<.0001	1551.4	1799
		50	3724.7	63.05537	63176	59.07	<.0001	3601.1	3848.3
		100	7356.3	63.09819	63176	116.58	<.0001	7232.6	7479.9
	Phase 7	20	1306.6	63.18445	63176	20.68	<.0001	1182.8	1430.5
		50	2038.6	63.18445	63176	32.26	<.0001	1914.7	2162.4
		100	2749.3	63.09866	63176	43.57	<.0001	2625.6	2872.9
	Phase 9	20	1112.7	63.18492	63176	17.61	<.0001	988.9	1236.6
		50	1835.1	63.05513	63176	29.1	<.0001	1711.5	1958.7
		100	2324.9	63.14145	63176	36.82	<.0001	2201.2	2448.7
WVO B20 vs. Bxx	Phase 5	50	2049.5	63.05537	63176	32.5	<.0001	1925.9	2173.1
		100	5681.1	63.09819	63176	90.04	<.0001	5557.4	5804.7
	Phase 7	50	732	63.14122	63176	11.59	<.0001	608.2	855.7
		100	1442.6	63.05537	63176	22.88	<.0001	1319	1566.2
	Phase 9	50	722.4	63.18492	63176	11.43	<.0001	598.5	846.2
		100	1212.2	63.27106	63176	19.16	<.0001	1088.2	1336.2
WVO B50 vs. B100	Phase 5	100	3631.5	63.01228	63176	57.63	<.0001	3508	3755.1
	Phase 7	100	710.7	63.05537	63176	11.27	<.0001	587.1	834.3
	Phase 9	100	489.8	63.14145	63176	7.76	<.0001	366.1	613.6

Table C-8: CO pairwise Student's t-test summary statistics – Effect of BLEND on SOY runs

		Table C-8: CO ER Pairwise Student's t-test Full Summary Effect of Blend (Bio%) for SOY runs, by Phase							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange =** 0.0001 < p < 0.05		
		Bio%	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
SOY B0 vs. Bxx	Phase 5	10	-2907.3	70.34281	63176	-41.33	<.0001	-3045.2	-2769.5
		20	3289.9	64.21697	63176	51.23	<.0001	3164.1	3415.8
		50	6623.8	70.12545	63176	94.46	<.0001	6486.3	6761.2
		100	651.5	70.00811	63176	9.31	<.0001	514.2	788.7
	Phase 7	10	-1052	70.11156	63176	-15	<.0001	-1189.4	-914.6
		20	2035.7	64.23044	63176	31.69	<.0001	1909.8	2161.6
		50	3478.8	69.97794	63176	49.71	<.0001	3341.6	3615.9
		100	931.5	68.74587	63176	13.55	<.0001	796.8	1066.2
	Phase 9	10	-763.1	69.78478	63176	-10.94	<.0001	-899.9	-626.4
		20	1004.1	63.99257	63176	15.69	<.0001	878.7	1129.5
		50	1810.2	69.92094	63176	25.89	<.0001	1673.1	1947.2
		100	658.3	69.4833	63176	9.47	<.0001	522.2	794.5
SOY B10 vs. Bxx	Phase 5	20	6197.3	55.9091	63176	110.85	<.0001	6087.7	6306.8
		50	9531.1	62.6066	63176	152.24	<.0001	9408.4	9653.8
		100	3558.8	62.47514	63176	56.96	<.0001	3436.3	3681.2
	Phase 7	20	3087.7	55.89286	63176	55.24	<.0001	2978.1	3197.2
		50	4530.8	62.41294	63176	72.59	<.0001	4408.4	4653.1
		100	1983.5	61.02832	63176	32.5	<.0001	1863.9	2103.1
	Phase 9	20	1767.2	55.97264	63176	31.57	<.0001	1657.5	1876.9
		50	2573.3	62.66438	63176	41.06	<.0001	2450.5	2696.1
		100	1421.5	62.17569	63176	22.86	<.0001	1299.6	1543.4
SOY B20 vs. Bxx	Phase 5	50	3333.9	55.63538	63176	59.92	<.0001	3224.8	3442.9
		100	-2638.5	55.4874	63176	-47.55	<.0001	-2747.2	-2529.7
	Phase 7	50	1443.1	55.72516	63176	25.9	<.0001	1333.9	1552.3
		100	-1104.2	54.16988	63176	-20.38	<.0001	-1210.4	-998
	Phase 9	50	806.1	56.1423	63176	14.36	<.0001	696	916.1
		100	-345.7	55.59631	63176	-6.22	<.0001	-454.7	-236.8
SOY B50 vs. B100	Phase 5	100	-5972.3	62.23031	63176	-95.97	<.0001	-6094.3	-5850.3
	Phase 7	100	-2547.3	60.87478	63176	-41.84	<.0001	-2666.6	-2428
	Phase 9	100	-1151.8	62.32847	63176	-18.48	<.0001	-1274	-1029.7

Table C-9: CO pairwise Student's t-test summary statistics – Effect of PHASE and FEEDSTOCK

		Table C-9: CO ER Pairwise Student's t-test Full Summary Effect of Phase by Feedstock and Fuel Blend							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange** = 0.0001 < p < 0.05		
		Phase	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
WVO	B0	5 vs. 7	20368.6	44.45156	63176	458.22	<.0001	20281.5	20455.8
		5 vs. 9	24757.1	44.51127	63176	556.2	<.0001	24669.9	24844.4
		7 vs. 9	4388.5	44.36979	63176	98.91	<.0001	4301.5	4475.5
	B10	5 vs. 7	17536.7	63.18445	63176	277.55	<.0001	17412.8	17660.5
		5 vs. 9	21271.6	63.09819	63176	337.12	<.0001	21147.9	21395.3
		7 vs. 9	3734.9	63.14145	63176	59.15	<.0001	3611.2	3858.7
	B20	5 vs. 7	17168.1	63.14122	63176	271.9	<.0001	17044.3	17291.9
		5 vs. 9	20709.1	63.22789	63176	327.53	<.0001	20585.2	20833.1
		7 vs. 9	3541	63.22789	63176	56	<.0001	3417.1	3665
	B50	5 vs. 7	15850.5	63.05537	63176	251.38	<.0001	15727	15974.1
		5 vs. 9	19382	63.01228	63176	307.59	<.0001	19258.5	19505.5
		7 vs. 9	3531.4	63.09819	63176	55.97	<.0001	3407.8	3655.1
	B100	5 vs. 7	12929.7	63.01228	63176	205.19	<.0001	12806.2	13053.2
		5 vs. 9	16240.3	63.14145	63176	257.2	<.0001	16116.5	16364
		7 vs. 9	3310.6	63.09866	63176	52.47	<.0001	3186.9	3434.3
SOY	B0	5 vs. 7	15616	77.01711	63176	202.76	<.0001	15465.1	15767
		5 vs. 9	20220.6	76.74025	63176	263.49	<.0001	20070.2	20371
		7 vs. 9	4604.5	76.64593	63176	60.08	<.0001	4454.3	4754.8
	B10	5 vs. 7	17471.4	62.7065	63176	278.62	<.0001	17348.5	17594.3
		5 vs. 9	22364.7	62.68142	63176	356.8	<.0001	22241.9	22487.6
		7 vs. 9	4893.4	62.53757	63176	78.25	<.0001	4770.8	5016
	B20	5 vs. 7	14361.8	48.14284	63176	298.32	<.0001	14267.4	14456.1
		5 vs. 9	17934.7	48.26803	63176	371.57	<.0001	17840.1	18029.3
		7 vs. 9	3573	48.43553	63176	73.77	<.0001	3478	3667.9
	B50	5 vs. 7	12471	62.31257	63176	200.14	<.0001	12348.9	12593.2
		5 vs. 9	15406.9	62.58954	63176	246.16	<.0001	15284.3	15529.6
		7 vs. 9	2935.9	62.54	63176	46.94	<.0001	2813.3	3058.5
	B100	5 vs. 7	15896	60.79057	63176	261.49	<.0001	15776.9	16015.2
		5 vs. 9	20227.4	61.96772	63176	326.42	<.0001	20106	20348.9
		7 vs. 9	4331.4	60.65744	63176	71.41	<.0001	4212.5	4450.3
		Compared factor	**Effect of Feedstock by Fuel Blend and Phase**						
		Feedstock	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
B0	Phase 5	WVO vs. SOY	7094.7	62.98658	63176	112.64	<.0001	6971.3	7218.2
	Phase 7	WVO vs. SOY	2342.1	62.77155	63176	37.31	<.0001	2219.1	2465.1
	Phase 9	WVO vs. SOY	2558.1	62.47407	63176	40.95	<.0001	2435.7	2680.6
B10	Phase 5	WVO vs. SOY	-376.6	62.99576	63176	-5.98	<.0001	-500.1	-253.2
	Phase 7	WVO vs. SOY	-441.9	62.89606	63176	-7.03	<.0001	-565.2	-318.7
	Phase 9	WVO vs. SOY	716.5	62.78437	63176	11.41	<.0001	593.5	839.6
B20	Phase 5	WVO vs. SOY	4145.4	56.07294	63176	73.93	<.0001	4035.5	4255.3
	Phase 7	WVO vs. SOY	1339.1	56.21719	63176	23.82	<.0001	1228.9	1449.3
	Phase 9	WVO vs. SOY	1371	56.42158	63176	24.3	<.0001	1260.4	1481.6
B50	Phase 5	WVO vs. SOY	5429.8	62.66658	63176	86.65	<.0001	5306.9	5552.6
	Phase 7	WVO vs. SOY	2050.3	62.70355	63176	32.7	<.0001	1927.4	2173.2
	Phase 9	WVO vs. SOY	1454.7	62.93566	63176	23.11	<.0001	1331.4	1578.1
B100	Phase 5	WVO vs. SOY	-4174.1	62.57842	63176	-66.7	<.0001	-4296.7	-4051.4
	Phase 7	WVO vs. SOY	-1207.7	61.2371	63176	-19.72	<.0001	-1327.7	-1087.7
	Phase 9	WVO vs. SOY	-186.9	62.53625	63176	-2.99	0.0028	-309.5	-64.3

Table C-10: NO pairwise Student's t-test summary statistics – Effect of BLEND on WVO runs

		Table C-10: NO ER Pairwise Student's t-test Full Summary Effect of Blend (Bio%) for WVO runs, by Phase							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange** = 0.0001 < p < 0.05		
		Bio%	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
WVO B0 vs. Bxx	Phase 5	10	-43.4	47.83299	63176	-0.91	0.3639	-137.2	50.3
		20	-659.9	47.83299	63176	-13.8	<.0001	-753.6	-566.1
		50	-461.8	47.74618	63176	-9.67	<.0001	-555.4	-368.2
		100	-856.9	47.78949	63176	-17.93	<.0001	-950.6	-763.2
	Phase 7	10	1384.6	47.776	63176	28.98	<.0001	1290.9	1478.2
		20	-640.2	47.73221	63176	-13.41	<.0001	-733.7	-546.6
		50	236.3	47.73221	63176	4.95	<.0001	142.8	329.9
		100	-100.2	47.64523	63176	-2.1	**0.0355**	-193.6	-6.8
	Phase 9	10	2496.2	47.73125	63176	52.3	<.0001	2402.7	2589.8
		20	-2275.9	47.86251	63176	-47.55	<.0001	-2369.7	-2182
		50	-41.6	47.73125	63176	-0.87	0.3831	-135.2	51.9
		100	-2614.6	47.81856	63176	-54.68	<.0001	-2708.3	-2520.8
WVO B10 vs. Bxx	Phase 5	20	-616.4	55.25537	63176	-11.16	<.0001	-724.7	-508.1
		50	-418.4	55.18024	63176	-7.58	<.0001	-526.5	-310.2
		100	-813.5	55.21772	63176	-14.73	<.0001	-921.7	-705.3
	Phase 7	20	-2024.8	55.2932	63176	-36.62	<.0001	-2133.2	-1916.4
		50	-1148.2	55.2932	63176	-20.77	<.0001	-1256.6	-1039.9
		100	-1484.8	55.21813	63176	-26.89	<.0001	-1593	-1376.5
	Phase 9	20	-4772.1	55.29362	63176	-86.3	<.0001	-4880.5	-4663.7
		50	-2537.9	55.18004	63176	-45.99	<.0001	-2646	-2429.7
		100	-5110.8	55.25558	63176	-92.49	<.0001	-5219.1	-5002.5
WVO B20 vs. Bxx	Phase 5	50	198.1	55.18024	63176	3.59	**0.0003**	89.9	306.2
		100	-197.1	55.21772	63176	-3.57	**0.0004**	-305.3	-88.8
	Phase 7	50	876.5	55.25537	63176	15.86	<.0001	768.2	984.8
		100	540	55.18024	63176	9.79	<.0001	431.9	648.2
	Phase 9	50	2234.2	55.29362	63176	40.41	<.0001	2125.8	2342.6
		100	-338.7	55.369	63176	-6.12	<.0001	-447.2	-230.2
WVO B50 vs. B100	Phase 5	100	-395.1	55.14254	63176	-7.17	<.0001	-503.2	-287.1
	Phase 7	100	-336.5	55.18024	63176	-6.1	<.0001	-444.7	-228.4
	Phase 9	100	-2572.9	55.25558	63176	-46.56	<.0001	-2681.2	-2464.6

Table C-11: NO pairwise Student's t-test summary statistics – Effect of BLEND on SOY runs

		Table C-11: NO ER Pairwise Student's t-test Full Summary Effect of Blend (Bio%) for SOY runs, by Phase							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange** = 0.0001 < p < 0.05		
		Bio%	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
SOY B0 vs. Bxx	Phase 5	10	-51	61.55754	63176	-0.83	0.4077	-171.6	69.7
		20	-453.2	56.19677	63176	-8.07	<.0001	-563.4	-343.1
		50	-799.7	61.36733	63176	-13.03	<.0001	-920	-679.4
		100	-419.8	61.26464	63176	-6.85	<.0001	-539.9	-299.7
	Phase 7	10	-831.7	61.35517	63176	-13.56	<.0001	-952	-711.5
		20	-942.8	56.20856	63176	-16.77	<.0001	-1052.9	-832.6
		50	-1084.4	61.23824	63176	-17.71	<.0001	-1204.4	-964.4
		100	-1300.5	60.16004	63176	-21.62	<.0001	-1418.4	-1182.6
	Phase 9	10	-3115.9	61.06921	63176	-51.02	<.0001	-3235.6	-2996.2
		20	-2737.7	56.0004	63176	-48.89	<.0001	-2847.5	-2628
		50	-2662.8	61.18835	63176	-43.52	<.0001	-2782.8	-2542.9
		100	-6377.3	60.80538	63176	-104.88	<.0001	-6496.5	-6258.2
SOY B10 vs. Bxx	Phase 5	20	-402.3	48.92648	63176	-8.22	<.0001	-498.2	-306.4
		50	-748.7	54.78753	63176	-13.67	<.0001	-856.1	-641.4
		100	-368.8	54.67248	63176	-6.75	<.0001	-476	-261.7
	Phase 7	20	-111	48.91228	63176	-2.27	**0.0232**	-206.9	-15.2
		50	-252.7	54.61805	63176	-4.63	<.0001	-359.7	-145.6
		100	-468.8	53.40636	63176	-8.78	<.0001	-573.5	-364.1
	Phase 9	20	378.2	48.98209	63176	7.72	<.0001	282.2	474.2
		50	453.1	54.83808	63176	8.26	<.0001	345.6	560.6
		100	-3261.4	54.41043	63176	-59.94	<.0001	-3368	-3154.7
SOY B20 vs. Bxx	Phase 5	50	-346.5	48.68695	63176	-7.12	<.0001	-441.9	-251
		100	33.4	48.55745	63176	0.69	0.491	-61.7	128.6
	Phase 7	50	-141.6	48.76552	63176	-2.9	**0.0037**	-237.2	-46.1
		100	-357.8	47.40448	63176	-7.55	<.0001	-450.7	-264.8
	Phase 9	50	74.9	49.13056	63176	1.52	0.1274	-21.4	171.2
		100	-3639.6	48.65277	63176	-74.81	<.0001	-3735	-3544.2
SOY B50 vs. B100	Phase 5	100	379.9	54.45823	63176	6.98	<.0001	273.2	486.7
	Phase 7	100	-216.1	53.27199	63176	-4.06	<.0001	-320.5	-111.7
	Phase 9	100	-3714.5	54.54413	63176	-68.1	<.0001	-3821.4	-3607.6

Table C-12: NO pairwise Student's t-test summary statistics – Effect of PHASE and FEEDSTOCK

		Table C-11: NO ER Pairwise Student's t-test Full Summary Effect of Phase by Feedstock and Fuel Blend							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange** = 0.0001 < p < 0.05		
		Phase	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
WVO	B0	5 vs. 7	-8334.7	38.89991	63176	-214.26	<.0001	-8411	-8258.5
		5 vs. 9	-31360	38.95216	63176	-805.09	<.0001	-31436.4	-31283.7
		7 vs. 9	-23025.3	38.82835	63176	-593	<.0001	-23101.4	-22949.2
	B10	5 vs. 7	-6906.7	55.2932	63176	-124.91	<.0001	-7015.1	-6798.3
		5 vs. 9	-28820.4	55.21772	63176	-521.94	<.0001	-28928.6	-28712.1
		7 vs. 9	-21913.7	55.25558	63176	-396.59	<.0001	-22022	-21805.4
	B20	5 vs. 7	-8315	55.25537	63176	-150.48	<.0001	-8423.3	-8206.7
		5 vs. 9	-32976	55.33122	63176	-595.98	<.0001	-33084.5	-32867.6
		7 vs. 9	-24661	55.33122	63176	-445.7	<.0001	-24769.4	-24552.5
	B50	5 vs. 7	-7636.6	55.18024	63176	-138.39	<.0001	-7744.7	-7528.4
		5 vs. 9	-30939.9	55.14254	63176	-561.09	<.0001	-31048	-30831.8
		7 vs. 9	-23303.3	55.21772	63176	-422.03	<.0001	-23411.5	-23195.1
	B100	5 vs. 7	-7578	55.14254	63176	-137.43	<.0001	-7686	-7469.9
		5 vs. 9	-33117.7	55.25558	63176	-599.35	<.0001	-33226	-33009.4
		7 vs. 9	-25539.7	55.21813	63176	-462.52	<.0001	-25647.9	-25431.5
SOY	B0	5 vs. 7	-6076.3	67.39827	63176	-90.16	<.0001	-6208.4	-5944.2
		5 vs. 9	-22464.2	67.15599	63176	-334.51	<.0001	-22595.9	-22332.6
		7 vs. 9	-16387.9	67.07345	63176	-244.33	<.0001	-16519.4	-16256.5
	B10	5 vs. 7	-6857.1	54.87495	63176	-124.96	<.0001	-6964.6	-6749.5
		5 vs. 9	-25529.2	54.853	63176	-465.41	<.0001	-25636.7	-25421.7
		7 vs. 9	-18672.1	54.72711	63176	-341.19	<.0001	-18779.4	-18564.9
	B20	5 vs. 7	-6565.8	42.13018	63176	-155.85	<.0001	-6648.4	-6483.3
		5 vs. 9	-24748.7	42.23973	63176	-585.91	<.0001	-24831.5	-24665.9
		7 vs. 9	-18182.9	42.38631	63176	-428.98	<.0001	-18266	-18099.8
	B50	5 vs. 7	-6361	54.53021	63176	-116.65	<.0001	-6467.9	-6254.1
		5 vs. 9	-24327.4	54.77259	63176	-444.15	<.0001	-24434.7	-24220
		7 vs. 9	-17966.3	54.72924	63176	-328.28	<.0001	-18073.6	-17859.1
	B100	5 vs. 7	-6957	53.1983	63176	-130.78	<.0001	-7061.3	-6852.8
		5 vs. 9	-28421.8	54.22844	63176	-524.11	<.0001	-28528.1	-28315.5
		7 vs. 9	-21464.7	53.0818	63176	-404.37	<.0001	-21568.8	-21360.7
		Compared factor	**Effect of Feedstock by Fuel Blend and Phase**						
		Feedstock	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
B0	Phase 5	WVO vs. SOY	366.9	55.12005	63176	6.66	<.0001	258.9	475
	Phase 7	WVO vs. SOY	2625.3	54.93187	63176	47.79	<.0001	2517.7	2733
	Phase 9	WVO vs. SOY	9262.7	54.67155	63176	169.43	<.0001	9155.6	9369.9
B10	Phase 5	WVO vs. SOY	359.4	55.12808	63176	6.52	<.0001	251.3	467.4
	Phase 7	WVO vs. SOY	409	55.04083	63176	7.43	<.0001	301.1	516.9
	Phase 9	WVO vs. SOY	3650.5	54.94309	63176	66.44	<.0001	3542.9	3758.2
B20	Phase 5	WVO vs. SOY	573.5	49.06986	63176	11.69	<.0001	477.4	669.7
	Phase 7	WVO vs. SOY	2322.8	49.1961	63176	47.21	<.0001	2226.3	2419.2
	Phase 9	WVO vs. SOY	8800.8	49.37496	63176	178.25	<.0001	8704.1	8897.6
B50	Phase 5	WVO vs. SOY	29	54.84001	63176	0.53	0.597	-78.5	136.5
	Phase 7	WVO vs. SOY	1304.6	54.87236	63176	23.77	<.0001	1197	1412.1
	Phase 9	WVO vs. SOY	6641.5	55.07549	63176	120.59	<.0001	6533.6	6749.5
B100	Phase 5	WVO vs. SOY	804.1	54.76286	63176	14.68	<.0001	696.7	911.4
	Phase 7	WVO vs. SOY	1425	53.58907	63176	26.59	<.0001	1319.9	1530
	Phase 9	WVO vs. SOY	5500	54.72596	63176	100.5	<.0001	5392.7	5607.2

Table C-13: NO_2 pairwise Student's t-test summary statistics – Effect of BLEND on WVO runs

		Table C-13: NO_2 ER Pairwise Student's t-test Full Summary Effect of Blend (Bio%) for WVO runs, by Phase							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange =** 0.0001 < p < 0.05		
		Bio%	**Difference**	**Std Error**	**DF**	**t Ratio**	**Prob > |t|**	**Lower 95%**	**Upper 95%**
WVO B0 vs. Bxx	Phase 5	10	263.21	9.99736	63176	26.33	<.0001	243.62	282.81
		20	-253.41	9.99736	63176	-25.35	<.0001	-273.01	-233.82
		50	158.36	9.97922	63176	15.87	<.0001	138.8	177.92
		100	87.79	9.98827	63176	8.79	<.0001	68.21	107.37
	Phase 7	10	521.42	9.98545	63176	52.22	<.0001	501.85	540.99
		20	482.27	9.9763	63176	48.34	<.0001	462.71	501.82
		50	905.14	9.9763	63176	90.73	<.0001	885.59	924.69
		100	1056.78	9.95812	63176	106.12	<.0001	1037.26	1076.3
	Phase 9	10	592.43	9.9761	63176	59.39	<.0001	572.88	611.98
		20	568.89	10.00353	63176	56.87	<.0001	549.28	588.5
		50	1204.47	9.9761	63176	120.74	<.0001	1184.92	1224.02
		100	1177.71	9.99435	63176	117.84	<.0001	1158.13	1197.3
WVO B10 vs. Bxx	Phase 5	20	-516.62	11.54868	63176	-44.73	<.0001	-539.26	-493.99
		50	-104.85	11.53298	63176	-9.09	<.0001	-127.46	-82.25
		100	-175.42	11.54081	63176	-15.2	<.0001	-198.04	-152.8
	Phase 7	20	-39.15	11.55659	63176	-3.39	0.0007	-61.8	-16.5
		50	383.72	11.55659	63176	33.2	<.0001	361.07	406.37
		100	535.36	11.5409	63176	46.39	<.0001	512.74	557.98
	Phase 9	20	-23.54	11.55668	63176	-2.04	0.0416	-46.19	-0.89
		50	612.04	11.53294	63176	53.07	<.0001	589.43	634.64
		100	585.28	11.54872	63176	50.68	<.0001	562.65	607.92
WVO B20 vs. Bxx	Phase 5	50	411.77	11.53298	63176	35.7	<.0001	389.16	434.37
		100	341.2	11.54081	63176	29.56	<.0001	318.58	363.82
	Phase 7	50	422.87	11.54868	63176	36.62	<.0001	400.23	445.51
		100	574.51	11.53298	63176	49.81	<.0001	551.91	597.12
	Phase 9	50	635.58	11.55668	63176	55	<.0001	612.93	658.23
		100	608.82	11.57243	63176	52.61	<.0001	586.14	631.51
WVO B50 vs. B100	Phase 5	100	-70.57	11.5251	63176	-6.12	<.0001	-93.16	-47.98
	Phase 7	100	151.64	11.53298	63176	13.15	<.0001	129.04	174.24
	Phase 9	100	-26.75	11.54872	63176	-2.32	0.0205	-49.39	-4.12

Table C-14: NO_2 pairwise Student's t-test summary statistics – Effect of BLEND on SOY runs

		Table C-14: NO_2 ER Pairwise Student's t-test Full Summary Effect of Blend (Bio%) for SOY runs, by Phase							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange =** 0.0001 < p < 0.05		
		Bio%	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
SOY B0 vs. Bxx	Phase 5	10	-301.15	12.86587	63176	-23.41	<.0001	-326.36	-275.93
		20	-296.33	11.74544	63176	-25.23	<.0001	-319.36	-273.31
		50	-318.79	12.82612	63176	-24.85	<.0001	-343.93	-293.65
		100	-954.9	12.80465	63176	-74.57	<.0001	-980	-929.8
	Phase 7	10	-344.24	12.82357	63176	-26.84	<.0001	-369.37	-319.11
		20	251.89	11.7479	63176	21.44	<.0001	228.87	274.92
		50	490.72	12.79914	63176	38.34	<.0001	465.64	515.81
		100	-239.36	12.57379	63176	-19.04	<.0001	-264	-214.71
	Phase 9	10	-602.63	12.76381	63176	-47.21	<.0001	-627.65	-577.62
		20	-24.9	11.7044	63176	-2.13	**0.0334**	-47.84	-1.96
		50	222.3	12.78871	63176	17.38	<.0001	197.23	247.36
		100	-33.93	12.70867	63176	-2.67	**0.0076**	-58.84	-9.02
SOY B10 vs. Bxx	Phase 5	20	4.81	10.22591	63176	0.47	0.6379	-15.23	24.86
		50	-17.64	11.4509	63176	-1.54	0.1234	-40.08	4.8
		100	-653.75	11.42685	63176	-57.21	<.0001	-676.15	-631.35
	Phase 7	20	596.13	10.22294	63176	58.31	<.0001	576.1	616.17
		50	834.96	11.41548	63176	73.14	<.0001	812.59	857.34
		100	104.88	11.16223	63176	9.4	<.0001	83	126.76
	Phase 9	20	577.73	10.23753	63176	56.43	<.0001	557.67	597.8
		50	824.93	11.46147	63176	71.97	<.0001	802.47	847.39
		100	568.71	11.37209	63176	50.01	<.0001	546.42	591
SOY B20 vs. Bxx	Phase 5	50	-22.45	10.17585	63176	-2.21	**0.0273**	-42.4	-2.51
		100	-658.56	10.14878	63176	-64.89	<.0001	-678.46	-638.67
	Phase 7	50	238.83	10.19227	63176	23.43	<.0001	218.85	258.81
		100	-491.25	9.9078	63176	-49.58	<.0001	-510.67	-471.83
	Phase 9	50	247.2	10.26856	63176	24.07	<.0001	227.07	267.32
		100	-9.03	10.1687	63176	-0.89	0.3748	-28.96	10.91
SOY B50 vs. B100	Phase 5	100	-636.11	11.38207	63176	-55.89	<.0001	-658.42	-613.8
	Phase 7	100	-730.08	11.13414	63176	-65.57	<.0001	-751.91	-708.26
	Phase 9	100	-256.22	11.40003	63176	-22.48	<.0001	-278.57	-233.88

Table C-15: NO_2 pairwise Student's t-test summary statistics – Effect of PHASE and FEEDSTOCK

		Table C-15: NO ER Pairwise Student's t-test Full Summary Effect of Phase by Feedstock and Fuel Blend							
		Compared factor	green = **REDUCTION** in emissions				red = **SIGNIFICANT** difference (<0.0001) **orange =** 0.0001 < p < 0.05		
		Phase	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
WVO	B0	5 vs. 7	-521.66	8.1303	63176	-64.16	<.0001	-537.6	-505.72
		5 vs. 9	440.9	8.14122	63176	54.16	<.0001	424.95	456.86
		7 vs. 9	962.56	8.11534	63176	118.61	<.0001	946.66	978.47
	B10	5 vs. 7	-263.45	11.55659	63176	-22.8	<.0001	-286.1	-240.8
		5 vs. 9	770.12	11.54081	63176	66.73	<.0001	747.5	792.74
		7 vs. 9	1033.58	11.54872	63176	89.5	<.0001	1010.94	1056.21
	B20	5 vs. 7	214.02	11.54868	63176	18.53	<.0001	191.38	236.65
		5 vs. 9	1263.2	11.56453	63176	109.23	<.0001	1240.54	1285.87
		7 vs. 9	1049.18	11.56453	63176	90.72	<.0001	1026.52	1071.85
	B50	5 vs. 7	225.12	11.53298	63176	19.52	<.0001	202.52	247.73
		5 vs. 9	1487.01	11.5251	63176	129.02	<.0001	1464.42	1509.6
		7 vs. 9	1261.89	11.54081	63176	109.34	<.0001	1239.27	1284.51
	B100	5 vs. 7	447.33	11.5251	63176	38.81	<.0001	424.74	469.92
		5 vs. 9	1530.83	11.54872	63176	132.55	<.0001	1508.19	1553.46
		7 vs. 9	1083.5	11.5409	63176	93.88	<.0001	1060.88	1106.12
SOY	B0	5 vs. 7	-642.25	14.08662	63176	-45.59	<.0001	-669.86	-614.64
		5 vs. 9	326.84	14.03598	63176	23.29	<.0001	299.33	354.35
		7 vs. 9	969.08	14.01873	63176	69.13	<.0001	941.61	996.56
	B10	5 vs. 7	-685.34	11.46917	63176	-59.75	<.0001	-707.82	-662.86
		5 vs. 9	25.35	11.46458	63176	2.21	0.027	2.88	47.82
		7 vs. 9	710.69	11.43827	63176	62.13	<.0001	688.27	733.11
	B20	5 vs. 7	-94.02	8.80544	63176	-10.68	<.0001	-111.28	-76.76
		5 vs. 9	598.27	8.82834	63176	67.77	<.0001	580.96	615.57
		7 vs. 9	692.29	8.85898	63176	78.15	<.0001	674.92	709.65
	B50	5 vs. 7	167.27	11.39712	63176	14.68	<.0001	144.93	189.6
		5 vs. 9	867.92	11.44778	63176	75.82	<.0001	845.48	890.36
		7 vs. 9	700.65	11.43872	63176	61.25	<.0001	678.23	723.07
	B100	5 vs. 7	73.29	11.11874	63176	6.59	<.0001	51.5	95.09
		5 vs. 9	1247.81	11.33405	63176	110.09	<.0001	1225.59	1270.02
		7 vs. 9	1174.51	11.09439	63176	105.87	<.0001	1152.77	1196.26
		Compared factor	**Effect of Feedstock by Fuel Blend and Phase**						
		Feedstock	***Difference***	***Std Error***	***DF***	***t Ratio***	***Prob > |t|***	***Lower 95%***	***Upper 95%***
B0	Phase 5	WVO vs. SOY	1151.63	11.5204	63176	99.96	<.0001	1129.05	1174.21
	Phase 7	WVO vs. SOY	1031.04	11.48107	63176	89.8	<.0001	1008.54	1053.54
	Phase 9	WVO vs. SOY	1037.56	11.42666	63176	90.8	<.0001	1015.16	1059.96
B10	Phase 5	WVO vs. SOY	587.27	11.52208	63176	50.97	<.0001	564.69	609.85
	Phase 7	WVO vs. SOY	165.38	11.50384	63176	14.38	<.0001	142.83	187.93
	Phase 9	WVO vs. SOY	-157.51	11.48341	63176	-13.72	<.0001	-180.01	-135
B20	Phase 5	WVO vs. SOY	1108.7	10.25588	63176	108.1	<.0001	1088.6	1128.81
	Phase 7	WVO vs. SOY	800.67	10.28226	63176	77.87	<.0001	780.51	820.82
	Phase 9	WVO vs. SOY	443.77	10.31964	63176	43	<.0001	423.54	463.99
B50	Phase 5	WVO vs. SOY	674.48	11.46187	63176	58.85	<.0001	652.02	696.95
	Phase 7	WVO vs. SOY	616.63	11.46863	63176	53.77	<.0001	594.15	639.1
	Phase 9	WVO vs. SOY	55.39	11.51109	63176	4.81	<.0001	32.83	77.95
B100	Phase 5	WVO vs. SOY	108.94	11.44574	63176	9.52	<.0001	86.5	131.37
	Phase 7	WVO vs. SOY	-265.1	11.20041	63176	-23.67	<.0001	-287.05	-243.14
	Phase 9	WVO vs. SOY	-174.08	11.43803	63176	-15.22	<.0001	-196.5	-151.66

D. Appendix D – Emission Rate Summary Tables for Each Pollutant

Table D-1: Mean formaldehyde emission rates (µg/s) and percent change from B0 (%)

FORMALDEHYDE									
Effects of Bio% & Phase on WVO Emission Rates									
	Phase 5			**Phase 7**			**Phase 9**		
	Mean	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**
B0	2236	2.72	0.0	322.7	2.70	0.0	134.2	2.71	0.0
B10	1780	3.85	20.4	303.7	3.86	5.88	115.0	3.85	14.3
B20	1560	3.85	30.2	265.8	3.85	17.6	101.3	3.86	24.5
B50	1388	3.84	38.0	279.4	3.85	13.4	88.28	3.85	34.2
B100	1097	3.85	50.9	320.2	3.84	0.785	91.29	3.86	32.0
Effects of Bio% & Phase on SOY Emission Rates									
	Phase 5			**Phase 7**			**Phase 9**		
	Mean	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**
B0	1827	3.71	0.0	258.3	3.70	0.0	100.9	3.67	0.0
B10	2098	3.02	-14.8	309.1	3.01	-19.7	91.70	3.01	9.09
B20	1376	2.31	24.7	222.6	2.32	13.8	70.20	2.34	30.4
B50	1080	3.00	40.9	220.1	2.99	14.8	66.86	3.02	33.7
B100	1492	2.99	18.3	375.4	2.86	-45.4	99.93	2.97	0.938

Table D-2: Mean carbon dioxide (CO2) emission rates (mg/s) and percent change from B0 (%)

CO_2									
Effects of Bio% & Phase on WVO Emission Rates									
	Phase 5			**Phase 7**			**Phase 9**		
	Mean	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**
B0	1310	3.35	0.0	1893	3.33	0.0	4370	3.34	0.0
B10	1345	4.74	-2.61	1933	4.75	-2.11	4550	4.74	-4.12
B20	1344	4.74	-2.56	1999	4.74	-5.63	4633	4.76	-6.03
B50	1289	4.73	1.64	2027	4.74	-7.11	4558	4.74	-4.31
B100	1248	4.74	4.77	2030	4.73	-7.24	4534	4.75	-3.76
Effects of Bio% & Phase on SOY Emission Rates									
	Phase 5			**Phase 7**			**Phase 9**		
	Mean	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**
B0	939.1	4.86	0.0	1405	4.85	0.0	3150	4.81	0.0
B10	970.3	3.96	-3.33	1469	3.94	-4.57	3373	3.94	-7.09
B20	992.9	3.02	-5.73	1527	3.05	-8.71	3443	3.06	-9.31
B50	976.6	3.93	-4.00	1532	3.92	-9.03	3317	3.96	-5.33
B100	1140	3.91	-21.4	1834	3.75	-30.6	4027	3.90	-27.9

Table D-3: Mean carbon monoxide (CO) emission rates (µg/s) and percent change from B0 (%)

CO									
Effects of Bio% & Phase on WVO Emission Rates									
	Phase 5			**Phase 7**			**Phase 9**		
	Mean	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**
B0	35493	33.9	0.0	15125	33.7	0.0	10736	33.8	0.0
B10	30929	48.0	12.9	13393	48.1	11.5	9658	47.9	10.0
B20	29254	48.0	17.6	12086	48.0	20.1	8545	48.1	20.4
B50	27205	47.9	23.4	11354	48.0	24.9	7823	47.9	27.1
B100	23573	47.9	33.6	10643	47.9	29.6	7333	48.1	31.7
Effects of Bio% & Phase on SOY Emission Rates									
	Phase 5			**Phase 7**			**Phase 9**		
	Mean	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**
B0	28399	49.7	0.0	12783	49.6	0.0	8178	49.2	0.0
B10	31306	40.5	-10.2	13835	40.3	-8.23	8941	40.3	-9.33
B20	25109	30.9	11.6	10747	31.1	15.9	7174	31.3	12.3
B50	21775	40.2	23.3	9304	40.1	27.2	6368	40.5	22.1
B100	27747	40.0	2.29	11851	38.3	7.29	7520	39.8	8.05

Table D-4: Mean nitrogen oxide (NO) emission rates (µg/s) and percent change from B0 (%)

NO									
Effects of Bio% & Phase on WVO Emission Rates									
	Phase 5			**Phase 7**			**Phase 9**		
	Mean	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**
B0	932.0	31.3	0.0	9267	31.08	0.0	32292	31.16	0.0
B10	975.4	44.3	-4.66	7882	44.34	14.94	29796	44.22	7.7
B20	1592	44.3	-70.8	9907	44.28	-6.9	34568	44.40	-7.0
B50	1394	44.2	-49.5	9030	44.28	2.6	32334	44.22	-0.1
B100	1789	44.2	-91.9	9367	44.16	-1.081	34907	44.34	-8.1
Effects of Bio% & Phase on SOY Emissions									
	Phase 5			**Phase 7**			**Phase 9**		
	Mean	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**
B0	565.1	39.6	0.0	6641	39.48	0.0	23029	39.20	0.0
B10	616.0	32.3	-9.02	7473	32.11	-12.5	26145	32.09	-13.5
B20	1018	24.6	-80.2	7584	24.80	-14.2	25767	24.92	-11.9
B50	1365	32.0	-142	7726	31.96	-16.3	25692	32.24	-11.6
B100	984.9	31.9	-74.3	7942	30.52	-19.6	29407	31.74	-27.7

Table D-5: Mean nitrogen dioxide (NO2) emission rates (µg/s) and percent change from B0 (%)

NO_2									
Effects of Bio% & Phase on WVO Emission Rates									
	Phase 5			**Phase 7**			**Phase 9**		
	Mean	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**
B0	4393	6.30	0.0	4915	6.26	0.0	3952	6.28	0.0
B10	4130	8.92	5.99	4393	8.93	10.6	3360	8.91	15.0
B20	4646	8.92	-5.77	4432	8.92	9.81	3383	8.95	14.4
B50	4235	8.90	3.60	4009	8.92	18.4	2748	8.91	30.5
B100	4305	8.91	2.00	3858	8.90	21.5	2774	8.93	29.8
Effects of Bio% & Phase on SOY Emissions									
	Phase 5			**Phase 7**			**Phase 9**		
	Mean	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**	**Mean**	**Std Error**	**% Δ from B0**
B0	3241	8.85	0.0	3883	8.83	0.0	2914	8.77	0.0
B10	3542	7.21	-9.29	4228	7.18	-8.86	3517	7.18	-20.7
B20	3538	5.51	-9.14	3632	5.55	6.49	2939	5.57	-0.854
B50	3560	7.16	-9.84	3393	7.15	12.6	2692	7.21	7.63
B100	4196	7.13	-29.5	4123	6.82	-6.16	2948	7.10	-1.16

Table D-6: Mean formaldehyde CO_2-normalized emission rates ($mg \cdot kg^{-1}$ CO_2)

Effects of Bio% & Phase on WVO Emission Rates			
	Phase 5	**Phase 7**	**Phase 9**
B0	1707	170.5	30.70
B10	1324	157.2	25.29
B20	1161	133.0	21.86
B50	1077	137.8	19.37
B100	879	157.7	20.13
Effects of Bio% & Phase on SOY Emission Rates			
	Phase 5	**Phase 7**	**Phase 9**
B0	1946	183.9	32.03
B10	2162	210.4	27.19
B20	1385	145.8	20.39
B50	1106	143.7	20.15
B100	1309	204.7	24.81

Table D-7: Mean CO CO_2- normalized emission rates ($mg \cdot kg^{-1}$ CO_2)

Effects of Bio% & Phase on WVO Emission Rates			
	Phase 5	**Phase 7**	**Phase 9**
B0	27088	7991	2457
B10	23004	6930	2123
B20	21770	6045	1844
B50	21108	5601	1716
B100	18892	5244	1617
Effects of Bio% & Phase on SOY Emission Rates			
	Phase 5	**Phase 7**	**Phase 9**
B0	30241	9100	2597
B10	32264	9418	2651
B20	25289	7037	2084
B50	22296	6075	1920
B100	24339	6461	1867

Table D-8: Mean NO CO_2-normalized emission rates ($mg \cdot kg^{-1}$ CO_2)

Effects of Bio% & Phase on WVO Emission Rates			
	Phase 5	**Phase 7**	**Phase 9**
B0	711.3	4896	7390
B10	725.5	4078	6549
B20	1185	4955	7461
B50	1081	4454	7093
B100	1434	4615	7699
Effects of Bio% & Phase on SOY Emission Rates			
	Phase 5	**Phase 7**	**Phase 9**
B0	601.7	4728	7312
B10	634.9	5087	7751
B20	1026	4966	7484
B50	1397	5044	7745
B100	863.9	4330	7303

Table D-9: Mean NO_2 CO_2- normalized emission rates ($mg \cdot kg^{-1}$ CO_2)

Effects of Bio% & Phase on WVO Emission Rates			
	Phase 5	**Phase 7**	**Phase 9**
B0	3353	2596	904.4
B10	3071	2273	738.4
B20	3458	2217	730.2
B50	3286	1978	602.7
B100	3450	1901	611.9
Effects of Bio% & Phase on SOY Emission Rates			
	Phase 5	**Phase 7**	**Phase 9**
B0	3452	2765	925.3
B10	3651	2878	1043
B20	3563	2378	853.7
B50	3645	2215	811.5
B100	3681	2248	732.2

E. Appendix E – Transient Phase Models

Table E-1: Transient phase models for every biodiesel feedstock and fuel blend combination, for all five pollutants

				Intercept				%Load				Corrected Engine Speed (rpm)				Exhaust Temp (°C)			
Feedstock	Bio%	Pollutant	Rsquare	Estimate	Std Error	t Ratio	Prob > |t|	Estimate	Std Error	t Ratio	Prob > |t|	Estimate	Std Error	t Ratio	Prob > |t|	Estimate	Std Error	t Ratio	Prob > |t|
WVO	0	CO	0.498	-4955.8	142.6	-34.75	<.0001	-103.0	2.476	-41.59	<.0001	11.38	0.0907	125.46	<.0001	1.527	1.211	1.26	0.2074
WVO	10	CO	0.571	-5257.3	169.8	-30.96	<.0001	-101.5	3.274	-31.01	<.0001	10.35	0.1101	94.07	<.0001	9.062	1.382	6.56	<.0001
WVO	20	CO	0.637	-5411.9	158.1	-34.23	<.0001	-96.88	3.138	-30.87	<.0001	10.64	0.1001	106.31	<.0001	1.971	1.267	1.56	0.1199
WVO	50	CO	0.613	-3821.1	151.2	-25.26	<.0001	-89.24	3.086	-28.91	<.0001	9.718	0.0971	100.05	<.0001	-4.216	1.219	-3.46	0.0005
WVO	100	CO	0.542	-2189.6	142.4	-15.37	<.0001	-71.79	2.775	-25.87	<.0001	7.852	0.0888	88.41	<.0001	-2.357	1.172	-2.01	0.0443
SOY	0	CO	0.486	-3274.0	215.0	-15.23	<.0001	-81.73	3.510	-23.29	<.0001	9.043	0.1279	70.69	<.0001	-1.834	1.951	-0.94	0.3474
SOY	10	CO	0.365	-2879.8	200.2	-14.38	<.0001	-71.97	2.971	-24.22	<.0001	8.509	0.1224	69.52	<.0001	3.873	1.833	2.11	0.0346
SOY	20	CO	0.578	-3937.0	110.6	-35.6	<.0001	-77.58	2.081	-37.28	<.0001	8.517	0.0679	125.37	<.0001	1.229	0.9710	1.27	0.2057
SOY	50	CO	0.513	-1810.5	132.8	-13.63	<.0001	-52.91	2.492	-21.23	<.0001	6.823	0.0812	83.98	<.0001	-6.713	1.164	-5.77	<.0001
SOY	100	CO	0.514	-3131.0	175.1	-17.88	<.0001	-92.17	3.417	-26.97	<.0001	9.379	0.1125	83.36	<.0001	-3.912	1.500	-2.61	0.0091
WVO	0	CO_2	0.863	-988.8	9.2	-107.14	<.0001	13.30	0.160	82.99	<.0001	1.089	0.0059	185.5	<.0001	1.760	0.0784	22.45	<.0001
WVO	10	CO_2	0.875	-969.9	13.4	-72.39	<.0001	13.50	0.258	52.25	<.0001	1.096	0.0087	126.22	<.0001	1.879	0.1091	17.23	<.0001
WVO	20	CO_2	0.890	-1012.8	13.1	-77.25	<.0001	15.87	0.260	60.96	<.0001	1.067	0.0083	128.49	<.0001	2.253	0.1051	21.44	<.0001
WVO	50	CO_2	0.891	-966.4	12.9	-74.8	<.0001	16.03	0.264	60.78	<.0001	1.038	0.0083	125.11	<.0001	2.133	0.1041	20.48	<.0001
WVO	100	CO_2	0.870	-969.4	13.9	-69.82	<.0001	13.92	0.271	51.46	<.0001	1.055	0.0087	121.92	<.0001	1.999	0.1142	17.5	<.0001
SOY	0	CO_2	0.855	-654.7	13.4	-48.93	<.0001	11.08	0.218	50.75	<.0001	0.7687	0.0080	96.56	<.0001	1.313	0.1214	10.81	<.0001
SOY	10	CO_2	0.831	-747.6	12.0	-62.35	<.0001	10.30	0.178	57.88	<.0001	0.8665	0.0073	118.26	<.0001	1.226	0.1097	11.17	<.0001
SOY	20	CO_2	0.873	-691.1	8.3	-82.97	<.0001	12.48	0.157	79.62	<.0001	0.7986	0.0051	156.07	<.0001	1.536	0.0731	21	<.0001
SOY	50	CO_2	0.871	-682.0	10.6	-64.18	<.0001	11.61	0.199	58.23	<.0001	0.7919	0.0065	121.82	<.0001	1.400	0.0932	15.03	<.0001
SOY	100	CO_2	0.866	-874.5	13.0	-67.03	<.0001	11.99	0.255	47.1	<.0001	0.9646	0.0084	115.09	<.0001	1.934	0.1118	17.3	<.0001
WVO	0	Formaldehyde	0.234	-87.9	6.8	-12.97	<.0001	-6.130	0.118	-52.1	<.0001	0.3451	0.0043	80.03	<.0001	-0.2555	0.0576	-4.44	<.0001
WVO	10	Formaldehyde	0.310	-113.2	7.2	-15.77	<.0001	-5.405	0.138	-39.05	<.0001	0.2997	0.0047	64.41	<.0001	0.1889	0.0584	3.23	0.0012
WVO	20	Formaldehyde	0.376	-105.7	6.7	-15.77	<.0001	-5.368	0.133	-40.34	<.0001	0.3170	0.0042	74.69	<.0001	-0.1957	0.0537	-3.64	0.0003
WVO	50	Formaldehyde	0.348	-30.8	6.5	-4.73	<.0001	-4.821	0.133	-36.24	<.0001	0.2933	0.0042	70.04	<.0001	-0.5763	0.0525	-10.97	<.0001

Table E-1 concluded				Intercept				%Load				Corrected Engine Speed (rpm)				Exhaust Temp (°C)			
Feedstock	Bio%	Pollutant	Rsquare	Estimate	Std Error	t Ratio	Prob > |t|	Estimate	Std Error	t Ratio	Prob > |t|	Estimate	Std Error	t Ratio	Prob > |t|	Estimate	Std Error	t Ratio	Prob > |t|
WVO	100	Formaldehyde	0.282	36.7	6.6	5.6	<.0001	-3.657	0.128	-28.58	<.0001	0.2455	0.0041	59.95	<.0001	-0.6035	0.0540	-11.17	<.0001
SOY	0	Formaldehyde	0.228	-46.7	9.6	-4.85	<.0001	-4.780	0.157	-30.42	<.0001	0.2633	0.0057	45.97	<.0001	-0.3544	0.0874	-4.06	<.0001
SOY	10	Formaldehyde	0.151	-20.4	9.0	-2.26	0.0236	-4.423	0.134	-33.1	<.0001	0.2357	0.0055	42.83	<.0001	0.0047	0.0824	0.06	0.9545
SOY	20	Formaldehyde	0.319	-73.3	4.5	-16.26	<.0001	-4.233	0.085	-49.87	<.0001	0.2423	0.0028	87.43	<.0001	-0.1512	0.0396	-3.82	0.0001
SOY	50	Formaldehyde	0.244	25.0	5.5	4.53	<.0001	-2.613	0.103	-25.26	<.0001	0.1854	0.0034	54.99	<.0001	-0.6090	0.0483	-12.61	<.0001
SOY	100	Formaldehyde	0.276	-10.8	8.5	-1.28	0.2007	-4.482	0.165	-27.1	<.0001	0.3132	0.0054	57.52	<.0001	-0.6935	0.0726	-9.55	<.0001
WVO	0	NO	0.721	-3206.0	75.8	-42.32	<.0001	130.56	1.315	99.26	<.0001	3.628	0.0482	75.26	<.0001	10.7862	0.6434	16.76	<.0001
WVO	10	NO	0.729	-2691.0	92.9	-28.95	<.0001	112.79	1.792	62.94	<.0001	2.909	0.0602	48.28	<.0001	12.9548	0.7565	17.12	<.0001
WVO	20	NO	0.744	-3272.6	106.3	-30.78	<.0001	136.33	2.110	64.6	<.0001	3.252	0.0673	48.32	<.0001	16.9287	0.8524	19.86	<.0001
WVO	50	NO	0.712	-3032.7	102.6	-29.55	<.0001	120.23	2.094	57.42	<.0001	2.924	0.0659	44.37	<.0001	14.5968	0.8270	17.65	<.0001
WVO	100	NO	0.706	-4017.7	107.9	-37.23	<.0001	106.57	2.103	50.69	<.0001	3.511	0.0673	52.18	<.0001	17.2659	0.8879	19.45	<.0001
SOY	0	NO	0.730	-2017.6	103.5	-19.5	<.0001	105.86	1.689	62.67	<.0001	2.269	0.0616	36.85	<.0001	10.4003	0.9391	11.07	<.0001
SOY	10	NO	0.718	-3634.1	101.7	-35.72	<.0001	101.88	1.509	67.5	<.0001	3.712	0.0622	59.7	<.0001	11.3839	0.9312	12.23	<.0001
SOY	20	NO	0.714	-1829.6	69.4	-26.35	<.0001	117.51	1.307	89.93	<.0001	2.210	0.0427	51.82	<.0001	11.7868	0.6097	19.33	<.0001
SOY	50	NO	0.729	-2598.4	85.4	-30.41	<.0001	97.94	1.603	61.08	<.0001	2.668	0.0523	51.06	<.0001	13.9869	0.7489	18.68	<.0001
SOY	100	NO	0.696	-3277.6	98.3	-33.33	<.0001	98.93	1.919	51.55	<.0001	2.795	0.0632	44.24	<.0001	16.2163	0.8425	19.25	<.0001
WVO	0	NO_2	0.665	-317.8	26.9	-11.8	<.0001	1.885	0.468	4.03	<.0001	2.449	0.0171	142.94	<.0001	-2.2446	0.2287	-9.82	<.0001
WVO	10	NO_2	0.693	-294.8	35.1	-8.41	<.0001	2.214	0.676	3.28	0.0011	2.197	0.0227	96.7	<.0001	-0.8580	0.2853	-3.01	0.0026
WVO	20	NO_2	0.743	-405.8	35.1	-11.57	<.0001	2.948	0.696	4.23	<.0001	2.402	0.0222	108.12	<.0001	-1.8035	0.2813	-6.41	<.0001
WVO	50	NO_2	0.704	50.0	34.2	1.46	0.1441	2.882	0.699	4.13	<.0001	2.141	0.0220	97.39	<.0001	-4.4056	0.2759	-15.97	<.0001
WVO	100	NO_2	0.685	32.0	32.7	0.98	0.3272	-0.828	0.637	-1.3	0.1934	2.025	0.0204	99.39	<.0001	-3.2767	0.2688	-12.19	<.0001
SOY	0	NO_2	0.669	-116.0	38.4	-3.02	0.0025	1.910	0.626	3.05	0.0023	1.862	0.0228	81.58	<.0001	-1.9269	0.3483	-5.53	<.0001
SOY	10	NO_2	0.608	-336.9	35.4	-9.51	<.0001	-0.116	0.525	-0.22	0.8256	2.018	0.0216	93.25	<.0001	-0.1379	0.3242	-0.43	0.6706
SOY	20	NO_2	0.697	-258.1	23.3	-11.08	<.0001	2.029	0.438	4.63	<.0001	1.843	0.0143	128.76	<.0001	-1.0003	0.2046	-4.89	<.0001
SOY	50	NO_2	0.677	-25.2	29.5	-0.85	0.3927	2.414	0.553	4.37	<.0001	1.721	0.0180	95.46	<.0001	-2.7108	0.2583	-10.5	<.0001
SOY	100	NO_2	0.688	-122.5	34.7	-3.53	0.0004	-1.267	0.677	-1.87	0.0613	2.142	0.0223	96.06	<.0001	-2.9172	0.2973	-9.81	<.0001

Note: The R^2 values listed in **Table E-1** describe how well the models fit the data used for producing the models.